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Journal of Petroleum Technology is published monthly. Domestic Subscription: North, South and Central America, $8; foreign, $9; to AIME members, $6, or $4 if in combination with subscription to either Journal of Metals or Mining Engineering. Single copies 75 cents; special issues, $1.50. Registered cable address AIME. Printed in USA. Copyright 1952 by American Institute of Mining & Metallurgical Engineers.

Official Publication

Petroleum Branch

American Institute of Mining & Metallurgical Engineers

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Journal of Petroleum Technology is published monthly by the American Institute of Mining and Metallurgical Engineers at 29 West 39th Street, New York 18, N. Y. Entered as second class matter January 31, 1949, at the post office at New York, N. Y., under the Act of March 3, 1879. Additional entry at Dallas, Texas.

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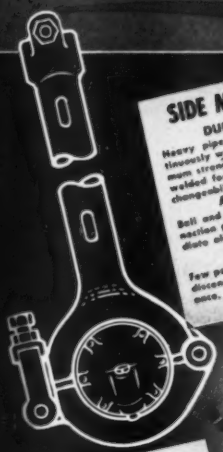

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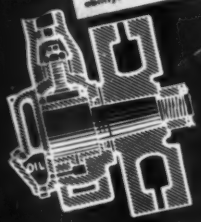

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THE PROFESSIONAL MAGAZINE FOR PETROLEUM ENGINEERS

Journal of Petroleum Technology

Vol. IV JANUARY, 1952 No. 1

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On the Cover Imperial-Redwater No. 58 emits clouds of steam in protest at Alberta, Canada's –40°F temperature. The frost covered drilling rig is surrounded by billowing steam clouds from the boilers and the derrick base itself where drilling fluid reaches the surface from far below ground. — Photo by Imperial Oil.

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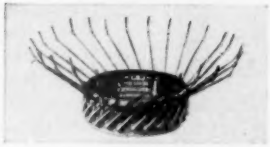

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Trends Toward Deeper Drilling Emphasize The Need for Extensive Laboratory and Field Tests to Evaluate More Fully Drilling Fluids.

The Effect of Circulating Media and Nozzle Design On Rock Bit Performance

By L. L. Payne
Hughes Tool Co.

IN an attempt to discover the effect of various circulating media and nozzle designs on rock bit performance, a series of laboratory and field tests have been conducted. Although it is possible to conduct experiments in the laboratory, actual conditions existing in the bored hole cannot be duplicated. Consequently, most laboratory results require confirmation from field application. However, notwithstanding the limitations, interesting and informative results obtained from laboratory tests may aid in planning future investigations.

CIRCULATION OF AIR OR GAS

Laboratory experiments conducted over several years proved that this type of medium was superior to a drilling fluid insofar as rock bit performance is considered. A special bit, mounted on a drill press and used for testing formation cores received from various fields, consistently indicated higher drillability than actually obtained in practice. In the laboratory, air was used to cool the cutters and to remove cuttings. Drilling was conducted under atmospheric pressure and this no doubt had a partial effect upon the more favorable drilling rate obtained in the laboratory.

Extensive field tests were conducted in the fall of 1949 to determine the relative merits of circulating air compared to water while drilling a soft limestone encountered in a Michigan limestone quarry. The initial test of circulating air confirmed previous laboratory indications. On-bottom drilling time per foot of hole was reduced 50 per cent compared to previous results obtained while circulating water. Bearing life materially increased while circulating air and the footage per bit was doubled over the results obtained with water. The on-bottom drilling cost per foot of hole was reduced by half.

A second field test was conducted in a Michigan dolomite quarry. On-bottom drilling time per foot of hole was reduced by 20 per cent and the amount of hole drilled per bit was doubled. A substantial reduction in total drilling cost per foot of hole resulted. The holes drilled vary in depth from 50 ft to 120 ft. At these depths pressure on the formation differed only slightly while drilling with water or air. The results proved rather conclusively that when drilling in the absence of sub-surface water flow a rock bit will perform better with air used in the circulating system.

During 1950 a major operator became interested in circulating air on seismograph rigs. Considerable difficulty had been encountered in Canada during the winter months because of the extreme cold freezing the circulating fluid. Furthermore, in many areas a ready source of water is not available and must be trucked to the rigs. Successful drilling with air would overcome these problems. Several field tests were made using a conventional truck mounted seismograph rig. In the absence of sub-surface water flows, circulation of air improved rock bit performance. When sub-surface waters were encountered the wetted formation cuttings were not efficiently lifted and severe balling occurred on the drill stem, drill collar, and bit body. Recorded results indicate usage of air in certain areas would improve rock bit performance and lower drilling cost.

The most extensive field tests of a gaseous circulating medium have been conducted during this year in the San Juan Basin located in Northwestern New Mexico. When rotary drilling into the producing gas pay with low water loss mud, or oil emulsion mud, damage to the producing zone and loss of returns were serious problems. Drilling in with cable tools became more or less a standard procedure, usually requiring 14 days for completion in addition to rigging up time. The El Paso Natural Gas Co., in seeking means of lowering completion cost and preventing damage to the producing zones, initiated a test of drilling in with rotary while circulating natural gas tapped from their high pressure gas line.

The initial test was highly successful, as shown by the following data. Three 6¼-in. tricone rock bits averaged 280 ft per bit at 40 ft per hour, compared to seven bits averaging 65 ft per bit at 5 ft per hour while circulating a low water loss drilling fluid. The volume of natural gas used in the test varied from approximately 1,000,000 cu ft per day to approximately 2,000,000 cu ft per day. While circulating 2,200,000 cu ft per day at 4,375 ft. from one and one-half to two minutes were required to clean the hole and while circulating 1,250,000 cu ft per day, from two to two and one-half minutes were required to clean the hole.

Since the initial test, several additional wells have been drilled in with natural gas circulation. In each case rock bit performance was materially improved in penetration rate and footage per bit.

CIRCULATION OF FLUIDS

Laboratory tests were performed to determine the effect on rate of penetration when the drilling fluid was changed from water to mud. Previous laboratory tests had confirmed numerous actual field observations that some muds adversely affected rock bit performance in drilling certain shales and sandstones. The results reported in this test were obtained while drilling on hard rock formations.

The results show a marked reduction in penetration rate when circulating a nine-lb per gal. 50-60 seconds per quart viscosity mud compared to water. An increase in load applied on the bit reduced the loss in penetration rate slightly.

This paper was presented at the Petroleum Branch, AIME, Fall Meeting in Oklahoma City, Okla., Oct. 3, 4, 5, 1951.

Load on Bit Lb	Drilling Rate — Ft per Hour Water	Mud	Per Cent Slower With Mud	Formation
10,000	3.83	2.99	21.9	Blair Dolomite
20,000	10.28	8.68	15.6	Blair Dolomite
10,000	1.66	1.17	29.5	Basalt
20,000	5.98	4.35	27.2	Basalt
20,000	6.07	3.13	48.5	Gray Granite
40,000	4.29	3.15	26.6	Quartzite

A series of laboratory tests was conducted to determine the effect of mud viscosity upon penetration rate. Water was used to establish a standard rate. Basalt, a high strength rock, was used for the test. The results appear in the following table.

Mud Viscosity Seconds Per Qt	Mud Slower than Water Per Cent
30-35	3.0
35-40	13.6
40-45	10.7
45-50	10.2
50-55	15.5
55-60	19.8
60-65	19.5
65-70	26.1

Although the test data are not consistent, it is quite obvious that pentration rates are seriously affected by mud viscosity. Field observations reflect an even greater penetration rate reduction resulting from changing a low viscosity high water loss mud over to a moderate viscosity lower water loss mud. A 50 per cent reduction in rate is not uncommon and test runs over short intervals have reflected a 200 per cent - 300 per cent faster penetration rate with water circulation compared to normal rate obtained with mud.

A series of laboratory drill rig tests was conducted to determine the effect of fluid pressure on the drillability of a formation. The drilling rate was held as near constant as possible and the load on the bit measured by means of strain gauges attached to a base plate supporting the formation. A $3\frac{7}{8}$-in. size bit was used in all tests. The table below is a record of results with 6 psi back pressure on formation.

Volume Circulated GPM	Average Drilling Rate Ft/Hr	Weight on Bit, Lb. Mud	Water	Per Cent More Weight to Drill with Mud	Formation
50	8.02	2020	1450	28.2	Sand Rock
50*	7.93	1897	1856	2.16	Sand Rock
60	7.75	2028	1915	5.57	Sand Rock
60	7.56	2467	2170	12.0	Soft Limestone
100	7.89	1775	1556	12.3	Soft Limestone

*Natural mud obtained from the field.

The test was repeated with 100 psi back pressure held on the formation. The data recorded appear in the table below.

Volume Circulated GPM	Average Drilling Rate Ft/Hr	Weight on Bit, Lbs Mud	Water	Per Cent More Weight to Drill with Mud	Formation
50	8.02	3500	1750	50	Sand Rock
50*	7.93	2470	1847	25.2	Sand Rock
60	7.75	2848	1890	33.6	Sand Rock
100	7.96	1830	1575	13.9	Sand Rock
60	7.56	3618	2535	30.0	Soft Limestone
100	7.89	1922	1795	6.6	Soft Limestone

*Natural mud obtained from the field.

Summary of Results:

1. More weight on the bit is required to maintain a given penetration rate when mud is circulated compared to water.
2. The effect of mud circulation differs greatly in drilling different formations.
3. Adverse effect of mud circulation decreased as circulation rate increased.
4. The percentage increase in weight required to maintain uniform drilling rate while circulating mud was greater when 100 psi back pressure was applied on the formation.

THE EFFECT OF OIL EMULSION MUD ON BIT PERFORMANCE

The introduction of oil into most types of water-base drilling fluids to give an oil emulsion mud has accomplished outstanding results in drilling various formations. The drilling rate of some formations has been doubled; bit bearings and cutting teeth have a longer life, resulting in more time on bottom. Early in 1949, Gulf Oil Corp. tested an 11 per cent to 17 per cent by volume emulsified oil in a 10.7 lb per gal lightly treated phosphate mud in drilling a well located in St. Martin Parish, La. The results are tabulated below.

Well	Section Drilled	Footage Drilled	Bits Used	Ft Per Bit	Rotating Hours	Bit Life Hours	Drilling Rate Ft/Hr
A	9428-10423	995	15	66.3	480.5	32	2.07
B	9420-10429	1009	8	126.1	416	52.1	2.43

Well A: Water mud.
Well B: 11% - 17% oil emulsion.

Summary of Results:

1. Saved seven bits and trips — a reduction of 46.6 per cent.
2. Saved 64.5 rotating hrs — 13.4 per cent.
3. Increased bit life 20.1 hrs — 62.8 per cent.
4. Increased footage per bit 59.8 ft — 90.5 per cent.
5. Increased drilling rate .36 ft/hr — 17.4 per cent.

The favorable results of the test in St. Martin Parish warranted further investigation of oil emulsion mud by Gulf Oil Corp. in the Bully Camp Field, Louisiana. In this test 15 per cent oil emulsion was added to the 15.2 lb per gal lime-starch mud while drilling at 9,008 ft. The data in the table reflects the effect on bit performance of drilling with water mud compared to drilling with 12 per cent-15 per cent oil emulsion mud.

Type Mud	Section Drilled	Footage Drilled	Bits Used	Ft Per Bit	Rotating Hours	Bit Life Hours	Drilling Rate Ft/Hr
Water-Mud	8503-9000	497	7	71	200	28.6	2.49
12-15% Oil Emulsion	9008-9500	492	2	246	87	43.5	5.66

Summary of Results:

1. Saved five bits and trips — a reduction of 71.5 per cent.
2. Saved 113 rotating hrs — 56.6 per cent.
3. Increased bit life 14.9 hrs — 52 per cent.
4. Increased footage per bit 175 ft — 246 per cent.
5. Increased drilling rate 3.17 ft/hr — 127.2 per cent.

Subsequent tests along the Gulf Coast of Texas comparing the effect of water mud and oil emulsion mud consistently showed marked improvement in bit performance resulting from the use of oil emulsion mud. Oil emulsion mud has had limited use in drilling the hard, high strength formations encountered in West Texas. The following table compares the results obtained on three wells drilled in the Yarborough-Allen Field, West Texas.

Well	Section Drilled	Footage Drilled	Bits Used	Ft Per Bit	Rotating Hours	Bit Life Hours	Drilling Rate Ft/Hr
A	8011-9157	1146	42	27.3	421	10.02	2.72
B	7947-9149	1162	50	23.2	467.5	9 35	2.49
C	8022-9217	1195	50	23.9	365.25	7.3	3.28

Well A: Water mud — lightly treated bentonite
Well B: Salt water starch
Well C: Lightly treated bentonite containing 5 per cent emulsified oil.

Summary of Results:

1. No saving in number of bits or trips.
2. Saved 56 rotating hours — 13.3 per cent.
3. A decrease in bit life.
4. Increased drilling rate 20.6 per cent compared to water mud and 31.7 per cent compared to salt water-starch mud.

Tests in the Pegasus Field located in West Texas showed a slight increase in average footage per bit and a marked increase in rate of penetration when drilling hard shale and lime. The following table shows the results obtained in drilling through a section of hard lime and shale on two wells also located in the Pegasus Field. The mud used in both cases was similar, except for the addition of 5 per cent oil emulsion to the mud used on Well *B*. Well *A* used water mud.

Well	Drilled Section	Footage Drilled	Bits Used	Ft Per Bit	Rotating Hours	Bit Life Hours	Drilling Rate Ft/Hr
A	10481-11574	1093	20	54.6	238.75	11.95	4.58
B	10480-11578	1098	18	61.0	227	12.60	4.84

Summary of Results:

1. Saved two bits and trips — a reduction of 10 per cent.
2. Saved 11.75 rotating hrs — 4.92 per cent.
3. Increased bit life .65 hrs — 5.44 per cent.
4. Increased footage per bit — 6.4 ft — 11.7 per cent.
5. Increased drilling rate .26 ft/hr — 5.68 per cent.

The following table shows the results obtained in drilling the Devonian section which consists of hard lime and varying concentrations of chert. A water mud was used on Well *A*. The mud on Well *B* was a similar mud with 7 per cent - 10 per cent emulsified oil added.

Well	Section Drilled	Footage Drilled	Bits Used	Ft Per Bit	Rotating Hours	Bit Life Hours	Drilling Rate Ft/Hr
A	11241-12353	1112	69	16.15	375.25	5.44	2.97
B	11281-12372	1091	52	21.00	340.00	6.55	3.22
Well A: 3 bits pulled for drill stem test.							
Well B: 5 bits pulled for drill stem test.							

Summary of Results:

1. Saved 17 bits and trips — a reduction of 29.6 per cent.
2. Saved 35 rotating hrs — 9.35 per cent.
3. Increased bit life 1.11 hrs — 20.4 per cent.
4. Increased footage per bit — 4.85 ft — 30 per cent.
5. Increased drilling rate .25 ft/hr — 8.4 per cent.
6. Greatest improvement in bit life and drilling rate was noted in sections containing chert.

In Stephens County, Okla., a large number of 3,000-ft wells have been drilled with emulsion mud. Numerous cases are on record showing penetration rate increases of 100 per cent to 200 per cent and bit requirement reduction of 30 per cent to 50 per cent.

The recorded data obtained from numerous wells drilled with water base mud and with oil emulsion mud show that bit performance, in general, is definitely improved when oil emulsion mud is in the system. The degree of improvement differs widely. The greatest improvement appears to be in drilling low strength, relatively soft or plastic shales. The improvement in drilling hard, tough, high strength formations such as lime or dolomite is not as great as when drilling a hard, friable formation such as chert. The reason oil emulsion mud increases the rate of drilling and the effective bit life is not definitely known. It appears that several factors contribute:

1. Reduction of torque and hole friction. The weight indicator more accurately shows the load applied on the bit.
2. The wettings of the cutting teeth by the emulsified oil prevents loose formation cuttings from adhering to the cutters so that virgin formation is drilled with each revolution of the bit.
3. Lubricating quality of the oil increases bearing life and apparently decreases the formational wear on the cutting surfaces.
4. Sealing properties of the oil may prevent water from filtering into the well bottom, and the virgin formation chips do not become mixed with the solids in the drilling mud to form a tacky mass through which the teeth would have to penetrate in drilling new formation.

EFFECT OF VARIOUS FLUIDS ON BIT BEARING LIFE

Laboratory tests have been conducted to compare the effect of different fluids on bearing life. Optimum performance resulted when circulating oil. On at least two occasions, the shortest bearing life was noted when operating the test in the presence of standard commercial muds obtained from drilling rigs in the West Texas and Arkansas-Louisiana-Texas areas. Since the commercial muds might have become contaminated with harmful ingredients during circulation under normal field drilling practice, we repeated the laboratory tests using fresh muds containing the mixture recommended by the manufacturer. The results compared favorably with our records of test on standard bentonite mud. One mud, as received from the field, reduced bearing life in the laboratory by approximately 50 per cent compared to standard bentonite mud.

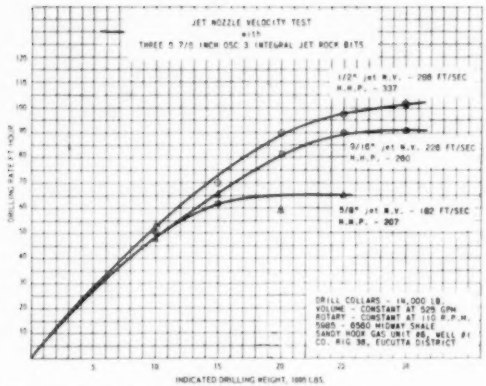
In field practice, an epidemic of premature bearing failures has been traced to the use of badly contaminated mud. These failures were eliminated by discarding the old mud and replacing with fresh mud. The bearing life, under the same operating conditions, increased to normal and rock bit performance reflected a reduction in cost. Oil base and oil emulsion muds are beneficial to bearing life. Field tests have consistently shown that oil base mud improved bearing life compared to other drilling fluids. In certain tests, bearing life was approximately twice that obtained with water base mud.

Oil base mud adversely affects rate of penetration and footage per bit. Its effect on bit performance is most pronounced in drilling certain shales and sand rocks. Field data has shown a penetration rate reduction of 50 per cent. In Rangely, Colo., rock bit performance records reflected a reduction in bit efficiency while drilling with oil base mud. Use of this type mud is justified only when factors other than rock bit performance require it.

NOZZLE DESIGN

The usual nozzle position causes the drilling fluid to impinge upon the cutters. A portion of the jet stream is deflected over the cutter surface and onto bottom for removal of loose cuttings. Field tests have established that a relatively large portion of the jet stream must impinge upon the outermost rows of gauge cutting teeth which are more prone to "ball up." Directing the major portion of the fluid upon the inner part of the cutter assembly deprived the outermost rows of adequate jetting action and packing of loose cuttings between adjacent teeth occurred. The size of nozzles used must be a compromise. A minimum diameter is desired in the interests of high jet velocity. However, jet velocity is limited because severe erosion of the cutter teeth is apt to occur when circulating abrasive laden mud.

Tests were conducted to determine the relative merits of jetting onto the cutters and jetting between the cutters while drilling a low strength, soft limestone. For each test the load required to drill at 20 ft/hr and at 100 ft/hr was recorded. Water was circulated using volumes in combination with nozzle size to produce approximately 250 ft/sec jet velocity.


JET NOZZLE VELOCITY TEST
WITH
THREE 7 7/8 INCH OSC 3 INTEGRAL JET ROCK BITS
1/2" jet N.V. - 208 FT/SEC
H.H.P. - 337
9/16" jet N.V. 208 FT/SEC
H.H.P. - 260
5/8" jet N.V. - 182 FT/SEC
H.H.P. - 207
DRILL COLLARS - 14,000 LB.
VOLUME - CONSTANT AT 525 GPM
ROTARY - CONSTANT AT 110 R.P.M.
5985 - 6560 MIDWAY SHALE
SANDY HOOK GAS UNIT #8, WELL #1
CO. RIG 38, EUCUTTA DISTRICT
DRILLING RATE FT/HOUR
INDICATED DRILLING WEIGHT, 1000 LBS.

The results of the tests indicated that:

1. Twenty-three per cent less weight was required to drill at 20 ft/hr with nozzles arranged to jet directly upon bottom compared to weight requirements on the same type bit having nozzles positioned to jet upon the cutters. Rotary speed was 100 rpm.
2. Ten per cent less weight was required to drill at 100 ft/hr while jetting directly upon bottom. Rotary speed was 375 rpm.
3. There was no appreciable difference in weight required to drill 100 ft/hr at 100 rpm. Although this test was limited to a few runs, the results warranted additional investigations.

A series of tests was conducted to evaluate nozzle position while drilling with water and with mud on high strength rocks. A jet velocity of approximately 230 ft/sec was used. These tests provided data from which the following conclusions were made.

1. That the bit having nozzles arranged to direct the drilling fluid onto bottom drilled faster while circulating water or low water loss mud.
2. While circulating water the penetration rate differed by 2.1 per cent.
3. While circulating mud the penetration rate differed by 16.3 per cent.
4. While circulating water through nozzles arranged to jet onto the cutters the average penetration rate was 5.72 ft/hr. Circulating mud reduced the penetration rate to 3.92 ft/hr, or a reduction in rate equal to 31.4 per cent.
5. That the average penetration rate of 5.84 ft/hr recorded while circulating water through nozzles arranged to jet onto bottom decreased to 4.56 ft/hr when mud was used in the system, or a reduction equal to 21.9 per cent.
6. That a loss in rock bit penetration rate resulting from the used of low water loss mud while drilling high strength formations will be decreased by using a rock bit having nozzles positioned to direct the fluid jet onto bottom.

The tests were repeated while drilling on gray granite with mud in the system. The penetration rate while jetting directly onto bottom was 4.03 ft/hr compared to 3.08 ft/hr while jetting onto the cutters.

The so-called "jet type" rock bit utilizes the energy available in the circulating system by directing the fluid through ports of reduced diameter positioned so that the high velocity jets clear the rolling cutters and impinge directly on bottom. Since the only washing action on the cutters results from the reaction splash across and off bottom, it is essential that adequate jet velocity be established to clean bottom instantly of all loose formation.

In general, the use of high velocity fluid jets has resulted in improved rock bit performance compared to the same type rock bit having conventional nozzles positioned to jet on the cutters. Where consistent improvement has been noted, the records indicate the minimum jet velocity was not less than 190 ft/sec. The minimum for all formations and for all drilling fluids is not definitely known. The records reflect that good performance has in some instances been obtained with 175 ft/sec jet velocity. However, this velocity is inadequate for some conditions.

In running a jet type rock bit, the complete requirements of the circulating system should be determined. A large number of rigs, particularly power rigs, having pumps and prime movers suitable for circulating through standard type water courses will require equipment changes if full benefit is to be realized from jet rock bits. In many cases, the sizes of liners normally used when drilling with rock bits having nozzles positioned to jet on the cutters are too large for drilling with jet rock bits. The following tabulation shows the approximate pressure drop across a conventional drilled water course (orifice coefficient .80), and across a jet type nozzle having three one-half in. ID jets (orifice coefficient .95), when circulating various volumes of 9.5 lb mud.

Volume Circulated GPM	Nozzle Pressure 3 - ½" Jets	Drop, psi DWC	Difference psi	½" Jet Velocity Ft/sec
350	310	125	185	190
375	355	140	215	205
400	405	160	245	220
450	510	200	310	245
500	630	250	380	270

When the additional pressure required to circulate a given volume of fluid through high velocity jet nozzles is added to the pressure required for circulation through the balance of the system, the total pressure required may exceed the capacity of the pump or prime mover.

For example: Drilling an 8¾-in. size hole at 6,350 ft and circulating 450 gal/min of 9.5 lb/gal mud through 4½-in. OD drill pipe; 360 ft of 6¼-in. OD by 2¼-in. ID drill collars with a conventional type water course in the bit would require a pump discharge pressure of approximately 1,140 psi. Under the same conditions, a bit having three ½-in. ID nozzles would require a pump discharge pressure of approximately 1,450 psi. Prime mover horsepower requirements would increase from approximately 390 to 500. If the additional pressure required for high velocity jet bit operation exceeds the capacity of the pump or the prime mover, the problem may be one of selecting a liner size which will provide the volume required for efficient jet bit operation and still permit use of the pump or prime mover. Since 450 gal/min gives a return velocity of 200 ft/min, a moderate reduction in return velocity can be made.

Suppose we decide on 220 ft/sec jet velocity. The required volume of fluid circulated will be 400 gal/min. If the pump had an 18-in. stroke and were operating at 52 strokes per minute, 6½-in. ID liners would be required to produce 450 gal/min (allowing 10 per cent for slip). In reducing the volume to 400 gal/min, 6-in. liners and 55 strokes per min would be required (allowing 10 per cent for slip). The return velocity up the annulus would be 177 ft/min. This is well within the range of accepted practice. The discharge pressure resulting would be approximately 1,170 psi. Approximately 360 hp would be required from the prime mover.

The reduction in liner size would prevent overloading the pump or engine and still provide adequate volume of circulating fluid for jet bit operation. Since power pumps are designed to withstand a maximum discharge pressure for a given liner size, the components of the circulating system should be selected so that total fluid friction losses will not exceed the maximum safe operating pressure. This control, in some cases, can be obtained by selection of nozzle diameter; in other cases liner size in the solution. A third choice is drill pipe size. The following friction loss inside drill stem reflects the marked difference in pressure required to circulate a given volume of fluid having a weight of 9.5 lb/gal and a viscosity of three centipoises.

Size of Drill Stem	Volume Circulated GPM	Frictional Loss — psi Per 1,000 Ft	Per 6,000 Ft
3½" IF	375	250	1,500
4" FH	375	100	600
4½" XH	375	55	330
3½" IF	500	440	2,640
4" FH	500	190	1,140
4½" XH	500	95	570

Rock bits having high velocity nozzles are much less flexible than standard bits, and minimum hydraulic requirements will exceed the capacity of many rigs. Reduction in pump liner size will not solve the problem in all cases, since the return velocity up the annulus would be inadequate for efficient lifting of cuttings. The size of hole being drilled may prevent the use of a larger size drill stem, thereby preventing a desired reduction in friction loss down the pipe to compensate for the additional pressure required to circulate through the jet bit nozzles.

CONCLUSIONS

1. A gaseous medium such as air or natural gas is the optimum substance to circulate for attaining maximum rock bit performance.
2. Rock bit performance is improved when drilling with water as compared to mud.
3. Oil emulsion mud improves performance in certain formations compared to water base muds.
4. Oil base mud retards bit performance in certain formations.
5. Rock bit bearing life is materially shortened by contamination of the drilling fluid with corrosive elements, *e.g.*, salt or hydrogen sulfide.
6. Nozzle position has a bearing on rock bit performance.
7. Nozzle design affects hydraulic requirements.

ACKNOWLEDGMENT

The author wishes to thank Hughes Tool Co. for the laboratory data included in this report and for permission to publish this paper.

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DISCUSSION

By George E. Cannon, Humble Oil and Refining Co., Houston, Tex., Member AIME

The paper presented by Payne points out in part the problem with which drilling and operating personnel are becoming more and more concerned — drilling wells faster and cheaper. In this case, the effect of circulating media and nozzle design on rock bit performance is considered. It should perhaps be emphasized that these are only two of the factors which affect rock bit performance. On the other hand, they are important especially when considered in connection with the other factors which affect rock bit performance, such as bit weight, rotary speed and formation hardness; and their connection to these other factors should be kept in mind when studying this paper.

Payne has very logically divided drilling fluids into two classes, namely, air or gas and liquids such as water and mud. We have done no work in the field of air or gas drilling but have followed the results obtained by other operators with great interest. The results obtained to date certainly indicate that this field holds great promise under certain conditions.

In the field of mud and water drilling, we are making quite an extensive investigation and have accumulated considerable experimental and routine drilling data. Our results may be summarized as follows:

1. We have found no liquid which will drill faster than water.
2. The primary property of drilling muds which causes a decrease in rock bit pentration rates appears to be weight or solid content.
3. Penetration rates appear to decrease when drilling with muds having low water loss.
4. High funnel viscosity or gel appears to have little or no effect on penetration rates unless these properties are due to high solid content.

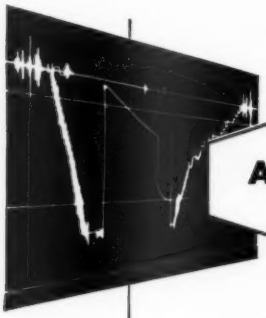
Since the test data presented by Payne on the effect of mud viscosity do not indicate the range of the mud weights used, it may be assumed that perhaps a variation in mud weight rather than viscosity caused the difference in penetration rates shown. In general, however, it may be stated that our experience substantiates the conclusions presented by Payne in his summary of results.

It is our belief that drilling fluids affect penetration rates in two different ways: The first of these is the effect they have on the instantaneous cutting action of the bit and upon its tendency to ball up; the second is the property of these fluids which controls the amount of lubrication and consequent drag in the hole. Our tests indicate that oil and oil emulsion muds retard the instantaneous cutting action in the same manner as conventional muds, but that due to their lubricating action, a greater proportion of the indicated bit weight is actually applied at the bit and that this is the reason that increased penetrating rates have been indicated by oil emulsion muds.

With regard to nozzle design, or perhaps more properly, nozzle utilization, it has been our experience that penetration rates have been uniformly increased by the proper use of jet bits. To supplement the data presented on circulating water using jet bits, a field test utilizing the duplex sub to drill a hard lime formation in West Texas showed that the jets have increased penetration rates, compared to those obtained with conventional water courses, from 10.5 to 30.7 per cent. The average increase obtained was 19.7 per cent.

To obtain the full advantage from the use of jet bits with any circulating medium requires that the maximum weight, just short of the balling-up point, must be carried. This is clearly indicated in the figure. If a weight on the bit, in this

Continued on Page 8, Section 2



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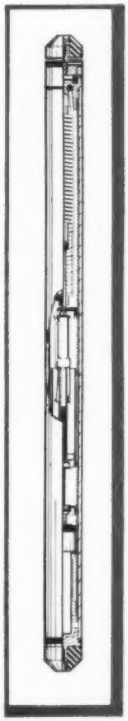

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Here Is What the Gas Industry Is Doing To Meet Demand and Necessity in One of the Fastest Growing Industrial Communities in the World.

Gas Supply and Requirements in California

By S. A. Bradfield
Southern California Gas Co.

TO understand properly the gas supply and demand situation in California one significant fact must be kept in mind: To the California householder, gas is the universal fuel. He looks to the state's gas utility companies to supply him with fuel for house heating, cooking and water heating, and to a somewhat lesser extent, refrigeration. His dependence on gas is traditional since California, unlike many other parts of the country, does not have major coal deposits.

California's cities are young, almost as young as the petroleum industry which supplies them with natural gas. The major portion of the state's growth has taken place since the turn of the century, particularly in the more populous southern half. The two world wars, the intervening period of boom and depression, and the post-World War II period have seen an unprecedented population increase and the development of an enormous west coast industrial empire. Fuel for both domestic and industrial growth has been supplied almost exclusively by the expanding petroleum industry through equally expanding facilities of the state's gas utility companies. To tell the story of the growth in California's gas requirements is the prime purpose of this paper.

Increase in Requirements

California's modern history is the story of many booms, but it was not until the first World War that its major industrialization and attendant domestic growth began. In 1920, the beginning of Southern California's greatest period of development, the state's population was 3,426,861. During the ensuing 30 years, population more than tripled to a present total of 10,586,223.

The most rapid increase in population has occurred in the southern portion of the state, including Los Angeles and contiguous territory. The 14 counties comprising the southern half of California have increased in population from 1,512,839 in 1920 to 6,095,394 in 1950.

Though the increase in California's population has been rapid, the use of natural gas has more than kept pace. In 1935 there were 1,486,640 general service customers in the state who consumed 71,638,340 Mcf of gas. In 1950, there were 2,880,180 who used 249,315,565 Mcf, an increase in the number of customers of 93 per cent but an increase in gas consumption of 248 per cent. Obviously, the increased number of gas users does not tell the whole story of the firm gas load increase.

To further illustrate the increased gas usage by California householders, the average general service customer in Southern California used about 83 Mcf of gas during the relatively cold year of 1949. In 1940, a somewhat warmer year, he used only 58 Mcf, and it has been estimated that with weather conditions comparable to those experienced in 1949, he would have used 63 Mcf. In other words, the average general service customer in Southern California now uses approximately a third more gas than he used ten years ago. The increase in the northern part of the state has been even more pronounced (Fig. 1).

This increase, no doubt is due to several reasons. The wartime and post-war business conditions have had their effect, and possibly an even more important factor has been the post-war rush of home owners to install gas appliances for diversified uses.

Industrial Growth

Population and industrial development have increased concurrently throughout the state. However, as a prelude to any discussion of industrial gas usage, one point should be made clear: The primary obligation of gas utility companies throughout the state is to their "firm" customers, the householders and commercial establishments who use gas primarily for cooking, heating and water heating. Transmission and distribution facilities in general are designed for the purpose of meeting peak demands of firm customers.

California's major industrial expansion began with the first World War. Prior to that time, the state's industries had in general been small, and largely confined to activities dealing with agriculture and mining. With the major petroleum discoveries which were made during and immediately following World War I, a general industrial expansion began. This expansion gathered momentum shortly before the second World War. Contrary to expectations, there was no major slow-down after the war, but rather a return to a slightly higher than normal level of activity. With the development of the Korean situation, the rate of increase in industrial activity again soared in a manner reminiscent of 1940-41. Throughout this expansion period, the petroleum industry has remained one of the dominating factors in California's industrial economy. Obviously, increased industrial production represents an increased market for fuel. The production and refining of petroleum is no exception, and therein lies a most important consideration with respect to the California gas supply picture. Since a very large proportion of the natural gas produced in California comes from oil fields, much of the local supply is closely allied with the rate of oil production. The portion of this supply which is available to utility companies, however, is also related to the use of gas by the oil companies in production and refining operations. This use by the producers has increased tremendously during the last 10 years.

This paper was presented at the Petroleum Branch, AIME, Fall Meeting in Los Angeles, Calif., Oct. 26, 27, 1951, and at Oklahoma City, Okla., Oct. 3-5, 1951.

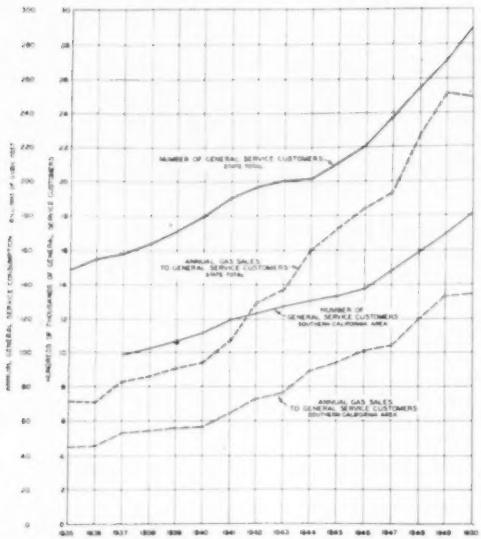

FIG. 1 — NUMBER OF GENERAL SERVICE CUSTOMERS AND TOTAL ANNUAL GAS USE BY THESE CUSTOMERS IN CALIFORNIA.

Gas Supply

Twenty-five years ago, California's gas supply was more than ample for all requirements. In the southern portion of the state, such fields as Signal Hill, Santa Fe Springs, and Dominguez provided an over abundance of gas to the Los Angeles area. The problems involved in getting this gas to market were minor too, because these major sources of supply were all within a stone's throw of the Los Angeles metropolitan area.

In the San Joaquin Valley to the north, Kettleman Hills, Elk Hills and the Midway-Sunset area near Taft provided large supplies for both Northern and Southern California, while the opening later of the Trico, McDonald Island and Rio Vista dry gas fields provided even greater supplies, while additional major volumes of gas were available in the Coastal area between Ventura and Santa Barbara.

Rapid development of the fields in and around Los Angeles, and the tremendous growth of this area, led to increasing dependence upon the San Joaquin Valley and Coastal production to meet Southern California's demands. By the beginning of World War II, about 60 per cent of the gas supply to the Los Angeles area market was being imported from other areas of the state. By this time also, Northern California was beginning to place more dependence upon the dry gas supplies from the Northern and Central San Joaquin Valley.

We have spoken of the increasing use of gas by oil companies in carrying out their producing and refining operations. In addition to increased plant and field fuel consumptions, ever increasing quanties of gas have been, and are being used for field pressure maintenance and repressuring operations.

California has enacted no formal legislation dealing with oil and gas conservation, but California oil producers are following a conservation program of considerable magnitude. Ultimately much of the gas currently being re-injected for pressure maintenance purposes will, no doubt, become available to consumers. Presently, however, the program has had the effect of removing from the market some 500 MMcf of gas daily (Fig. 2).

Because the market for gas has increased so greatly and because California supplies available to utility companies show a marked decline, it has been necessary for these companies to seek additional supplies outside the state.

The first importation of gas into California was undertaken jointly by Southern California Gas Co. and Southern Counties Gas Co. of California in collaboration with the El Paso Natural Gas Co. Under terms of the agreement among these three companies, the El Paso Natural Gas Co. built a pipeline to transport gas from West Texas to the Arizona-California border, and the two California companies constructed a pipeline to take the gas into the heart of the Southern California market area.

In the original plans, the California companies contemplated receiving 125 MMcf of gas daily during the first year of operation, 1947-48; 175 MMcf during the second, third and fourth years; and 305 MMcf daily in the fifth and succeeding years. However, the rapid and continuing growth in Southern California made it imperative that this timetable be stepped up.

First, delivery of the 305 MMcf/D was moved up from the end of 1952 to the beginning of 1949. Then, under a supplementary agreement, the El Paso Company undertook to supply an additional 100 MMcf/D as soon as the necessary additional facilities could be installed. Deliveries of 405 MMcf/D were begun in the summer of 1950 and are currently being made.

In the fall of 1950, also, the Pacific Gas and Electric Co. completed a pipeline from the San Francisco Bay area to the California-Arizona border to connect with El Paso's facilities. By November or December of 1951, it was expected that this line would deliver 400 MMcf/D to Northern California from West Texas and the San Juan Basin. To make possible these deliveries in addition to its supply to Southern California, El Paso Natural Gas Co. has paralleled nearly their entire main line system and has installed a new line from the San Juan Basin to the Arizona-California border.

In the light of most recent estimates of California's future gas requirements, Southern California Gas Co., Southern Counties Gas Co. and Pacific Gas and Electric Co. have requested El Paso Natural Gas Co. to increase deliveries into the state by 200 MMcf/D in the fall of 1952, and by an additional 100 MMcf/D in November, 1953. If current negotiations for the additional supply are successful, facilities for its delivery will be expanded by installation of additional pipeline and compressor station capacity during the next two years.

Load Equation

One of the major problems faced by the California utility companies is in the balancing of supply with demand on seasonal, daily and hourly bases.

The operation of a large pipeline, such as the Texas-California system, can be economical only under a high load factor. Also, California gas utility companies handle the maximum available quantities of California oil well gas production.

On the supply side, this means that large quantities of gas are received by the utility companies day in and day out throughout the year. Generally speaking, facilities are constructed for the purpose of meeting the peak day requirements of the firm gas customers. Peak days are rather infrequent but utility companies must be in position to supply these maximum demands.

As a result, for the greater part of the year, more gas is available than is required at the moment to supply firm demand. If the total annual supply is greater than the total

annual firm demand, gas is available to supply other than firm requirements.

Much of the industrial gas usage in California is on an interruptible basis. Industrial customers are supplied with gas as primary fuel with the understanding that service will be curtailed during periods when the gas is required for firm use. These industrial plants, of course, provide their own standby fuel supplies to meet these contingencies. This arrangement presently provides a very satisfactory cushion, and enables utility companies to maintain the required high load factor on their long transmission systems.

As the total annual supply approaches the total annual firm requirement, however, the amount of gas available for interruptible industrial use obviously decreases. Nevertheless, because of seasonal temperature variation, there will still be a large part of the year during which supply will exceed firm demand. Conversely, during winter months, the demand at times will exceed the available normal supply. To absorb the excess gas during summer and provide an adequate supply during winter, means of storing large volumes of gas must be provided.

Since the gas utility companies operating in the northern part of the state have had access to the major portion of the state's dry gas reserves, they have as yet not found it necessary to develop major seasonal storage. However, since the Southern California companies have had at their disposal only a relatively small supply from dry gas fields which could be shut in or withdrawn at will, they have been the first to make use of large storage projects.

La Goleta dry gas field, located on the coast north of Santa Barbara, is one such project. It was discovered in 1929 by General Petroleum Corp., and during the following 10 years, about 15 billion cu ft of gas was withdrawn to augment supplies for essential usage in Southern California during periods of heavy winter demand. The field, which is owned and operated by Pacific Lighting Gas Supply Co., a non-public utility, is used as an underground storage reservoir for locally produced gas. The reservoir has a working capacity of 10 billion cu ft between established pressure limits, and an estimated total capacity of 50 billion cu ft. During the summer months, gas from neighboring oil fields is purchased and stored by Pacific Lighting Gas Supply Co., and during winter periods of peak demand is delivered by them to the systems of Southern California Gas Co. and Southern Counties Gas Co. at rates as high as 375 MMcf/D.

A second similar underground storage operation is carried on by Southern California Gas Co. at the Playa del Rey oil field near the coast just west of Los Angeles.

The subterranean reservoir there is only a fraction as large as at La Goleta, having an estimated total capacity of $1^1/_4$ billion cu ft as compared to La Goleta's 50 billion. The smaller field, however, has a material advantage in being near the market area and immediately available for quick supplemental gas supply to meet operating emergencies and extreme peak hour demands.

Gas can be injected into Playa del Rey at rates up to 20 MMcf/D, and present facilities provide for withdrawal at a maximum daily rate of 120 MMcf. To provide for even greater flexibility in the use of the field, facilities are currently being installed which will approximately double the rate at which gas can be injected. This will permit operation of the project on a day-to-day basis somewhat similar to the operation of a conventional above ground holder. The working capacity of this reservoir, however, approximates one-half billion cu ft, the equivalent of 50 of our larger holders.

These two projects currently represent the major part of the underground storage operation in the state. As the annual firm requirements approach the annual primary gas supply, however, additional seasonal storage must be developed to equate supply and demand.

As another means of meeting peak hour and peak day requirements, the utility companies have built into the latest additions to their transmission pipeline systems, considerable quantities of storage capacity. As an example, the pipeline system of Southern California Co. and Southern Counties Gas Co. from the Arizona-California border to Los Angeles has a storage capacity of about 60 MMcf when operated on a pack and draught basis. Constant input of 405 MMcf/D can be maintained at the state boundary while withdrawals at the Los Angeles end may fluctuate widely depending upon prevailing load conditions.

To supplement all other supplies during hours of peak demand, all utility companies also maintain the conventional above ground high or low-pressure gas holders.

Supply vs Requirements — Present and Future

This year, thanks to the far-sightedness of leaders in the gas industry both on the coast and in the mid-continent area, California gas users are enjoying an adequate supply of fuel. During the unseasonably mild winter of 1950-51, even interruptible industrial customers enjoyed the use of gas to a greater extent than they had for several years. Because 1951 has been a much warmer than normal year throughout the state, however, the statistics relating to gas supply and demand for this year may be misleading.

Because of greatly increased military and defense activity on the coast, the California Public Utilities Commission early this year ordered an investigation "to ascertain the present and potential demands for and availability of gas in California, and the need for, and propriety of, emergency modifi-

Continued on Page 8, Section 2

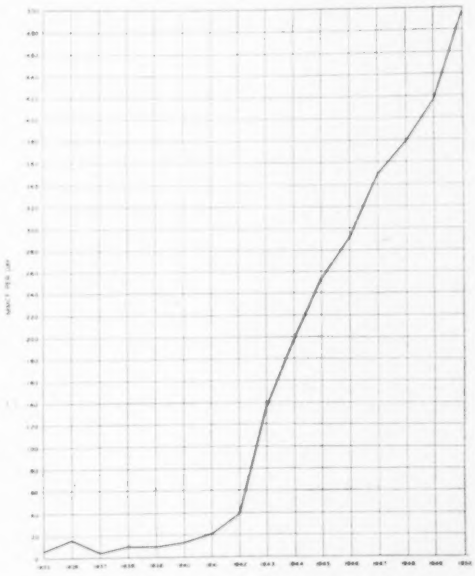

FIG. 2 — GAS INJECTED FOR REPRESSURING AND PRESSURE MAINTENANCE (MMcf/D)

BS&B 70G indirect heater on Carthage, Tex. system. (Right) a 10 year-old BS&B indirect heater still in use for auxiliary service.

BS&B 70 G INDIRECT HEATERS

Make Sense • Save Dollars

on This East Texas 12 Inch Gathering Line...

Putting the heat on the 40 Million CF of gas flowing daily through the 12 in. line of an extensive gathering system near Carthage, Texas, has been greatly simplified by the use of four BS&B Series 70 Giant heaters over a 12 mile stretch. With a 4 million BTU hourly input and a thermal efficiency better than 70%, these BS&B Giant indirect Heaters not only reduced the initial heater purchase and installation cost to a minimum but are saving money on fuel consumption and maintenance every day. They're constant proof that economy and efficiency are partners in BS&B oil field equipment.

7 ADVANTAGES OF BS&B "70" HEATERS

SAVES FUEL GAS—at rated capacity, the overall thermal efficiency is 70% or more—highest of any heater unit.

SAVES UNIT COST—"70" Series indirect heaters are fabricated in sizes ranging from 250,000 to 4,000,000 BTU input per hour—a heater for every gas and oil heating job.

SAVES MAINTENANCE COSTS—easier to service because firebox and flow coil can be pulled separately—from opposite ends.

SAFER WATER LEVELS—the exclusive BS&B Water Saver condenses hot water vapor, returns it to main water bath.

GREATER FLOW TUBE SURFACE—it's the square feet of transfer surface that counts—the BS&B flow coil offers more surface.

GREATER SAFETY—the gas and oil are completely sealed from firebox—surrounded by water; the even heat of water bath reduces scaling, prevents burnouts.

BS&B ENGINEERING SERVICE—always available, the highly skilled, prompt service of your nearby BS&B sales engineer—the engineering facilities of Black, Sivalls and Bryson's Oil and Gas Division at Oklahoma City—and the 35 efficiently staffed and equipped sales and engineering branches maintained by BS&B in the oil country.

70S (standard) and 70B (bantam) BS&B heaters at a South Texas wellhead, utilized with two-stage separation. The BS&B 70 series heater reputation for reliability has made it the most popular for field installations.

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The History and Modern Application of Gas Lift

Reported by R. H. Burke

Pacific Junior Group

Harry V. Eicher, Jr., gas lift engineer for Camco, Inc., in Houston, Tex., spoke on the development of gas lift equipment and processes to a meeting of the Pacific Junior Group recently, in Downey, Calif. Opening his discussion with remarks on the early applications of gas-lift, Eicher later discussed at length the various factors within the individual well which influence its usefulness. A condensation of his talk follows.

Air-lift, the grandfather of modern gas lift, was first used in Chemnity, Hungary, in 1782, to lift water from a flooded mine shaft. Large scale projects to lift water from mines were put to use in the latter part of the 19th century and the early part of the 20th century. Compressed air was used to empty water from flooded mines in Cuba, Mexico, Arizona and Pennsylvania many times during this period. The most famous of these mines was the Old Dominion Mine at Globe, Arizona, which had been flooded by heavy rainfall. The water was jetted out by means of compressed air and steam. During a six-month period 40,000,000 bbl of water were lifted from this mine and in one month 10,000,000 bbl were disposed of.

First Oil Well Gas Lift

The first application of gas-lift in the petroleum industry occurred in a well in Pennsylvania in 1864. This well caused a sensation because it had failed to produce on the beam pump. Failure was possibly caused by gas locking. On gas-lift, the well produced between 50 and 60 B/D of fluid. Several articles were written on this amazing new way of lifting oil with gas and one author went so far as to say that this method of producing would replace the conventional beam pump. Several months later, gas-lift was tried on other nearby wells with only fair results, and eventually the entire field was on the beam.

In 1902-1905, compressed air was used at Goose Creek, Hull, Humble, Orange, West Columbia and other fields in the Texas Gulf Coast where natural flow ceased or fluid volumes were not considered sufficient. In 1909, gas-lift was introduced in California at

HARRY V. EICHER, JR.

the Kern River Field. During the twilight stage of the wells this method of production proved quite satisfactory; however, it eventually had to be replaced by the beam pump.

In the early days of air-lift, compressors were almost always driven by steam furnished from boilers fired with the produced oil. When the production declined and insufficient oil was produced to fire the boilers, air-lift was abandoned. In 1925, the Jones method of re-cycling gas was introduced in California. From this stemmed the change from compressed air to compressed gas in large scale gas-lift projects. Late in 1926, gas-lift was tried in the Seminole Field in Oklahoma. Here for the first time studies were made on the efficiencies of gas-lift. Tests were made on the effect of bottom hole flowing pressure, size of eductor pipe and the effect of back pressure caused by high trap pressure, size and lengths of flow lines, right angle bends, and other relative data. About the same time, gas lift was introduced in California at the Long Beach, Rosecrans, Huntington Beach and Santa Fe Fields. The success of gas-lift in the early days of these fields and in the Seminole Field led to the introduction of gas-lift to West Texas and to various foreign countries, such as Peru, Romania, Trinidad and Venezuela.

All gas-lift mentioned up to this time was that of the continuous flow type, generally classified as U-tubing. It was accomplished by injecting gas into the tubing and producing through casing annulus, injecting gas through the casing and producing through the tubing, or injecting gas through a small parallel string of tubing and producing through the regular tubing. These methods were a far cry from modern gas-lift, but quite successful in certain wells.

Intermitting Developed

The decline in bottom hole pressures in the Seminole and Santa Fe fields introduced a new phase in gas-lifting: that of intermitting the gas into the well at the surface. In wells where the fluid volume was not great enough to justify continuous flow, this method saved large quantities of gas and in many instances increased the fluid production.

In 1930, conservation laws in several states establishing well allowables paved the way for the use of jet collars, perforated tubing and differential flow valves, commonly called kick-off valves. Differential valves and jet collars had been put to limited use in 1926 in the Corpus Christi area and in the later phases of lifting in the Seminole and Santa Fe Fields. However, the Oklahoma City Field was the first where valves were used to any great extent. Wells in this field were placed on a monthly prorated allowable. The wells flowed naturally and in most cases the production for the month was made in several days and the wells were shut-in the remainder of the month. The normal decline in the bottom hole pressure and the encroachment of waste soon changed this picture and many of the wells needed aid before they started to flow again. To help the well unload its dead fluid, several differential valves were placed in the tubing string. When the well was shut in, formation gas accumulated in the casing annulus supplying enough energy to resume flow if the fluid heads were not too great. By placing the valves at certain intervals, this casing gas was allowed to enter the tubing, thus unloading the heavy

fluid and putting the well in a flowing state. In time, gas had to be injected to keep the wells producing, and as the bottom hole pressure continued to decline and fluid production fell off, the wells were placed on surface controlled intermitting gas-lift. Several types of subsurface controlled intermitting gas-lift valves were used during this period. The Nixon surface controlled wire line valve was introduced here and the Acme macaroni valve was put to limited use. The Hughes plunger was used in many of these wells with a fair amount of success. Even so, the success in the gas-lift was not equal to the success of the beam pump, and the use of the pump became much greater.

Growth During World War II

With World War II demanding so much more of our oil, gas-lift became more and more popular. Also, less of the all important steel was used in gas-lifting than in any other form of artificial lift. At the close of the war, gas-lift manufacturers woke up to the fact that unless they could carry wells to depletion on gas-lift, it would not be a satisfactory method of artificial lift and would be eventually replaced by pumps. Valve manufacturers concentrated on making valves that would withstand the severest well conditions and abuse. During the war, bellows manufacturers had developed a very sturdy seamless bellows. This one item along with the development of new materials, such as tungsten carbide, has solved the problem of furnishing a durable power section for all recognized valves. Extensive studies have been made to determine where and when gas-lift equipment should be used.

Several important questions should be asked prior even to considering the use of the gas lift. The gas-lift engineer should then be able to recommend the type gas-lift that should be most applicable. He can also tell whether continuous flow or inttermittent flow type valves should be run and at what pressure these valves should be set.

Let us consider the gravity of the oil. Generally speaking, gas-lift should not be attempted in crudes with API gravities below 20°. An exception to this would be when the water percentage is above 85 per cent and large volumes of fluid must be lifted. Another exception to this general rule is where the well is producing pipe line oil, and water percentage will never be higher than 10 to 15 per cent. The reason for this caution is that low gravity crudes produced with water usually become emulsified. The addition of gas to this emulsion stirs this fluid to a very viscous substance closely resembling whipped cream and continuous gas-lift will not lift it. To overcome this problem, an intermitting flow installation is recommended.

Is paraffin a problem? Constant flow installations would seldom be recommended unless large volumes of fluid, which would be produced at high tubing temperature, would be lifted. In small wells making paraffin, only intermitting installations would be advised.

Generally speaking, wells troubled by sand are brought in by continuous flow. If the well is a small producer and continuous flow is uneconomical, we could commence intermitting it once the sand content fell below two or three per cent. If the fluid is mostly oil, as much as eight to ten per cent sand can be intermitted without the danger of bridging up the tubing.

We are also concerned with how much fluid is desired. First the operator will have to know how much the well is capable of making, how far it is necessary to lift and whether there will be sufficient energy to move this amount of fluid. The type of lift must also be decided, whether continuous or intermitting flow will give the most economical results. The source of gas will be important, for on intermitting flow normally a large supply of gas must be available for a short interval of time.

Two of the gas-lift companies are now developing an intermitting valve that may use the well's casing annulus for the storage chamber needed for intermitting.

Use of Continuous Flow

The total amount of fluid to be produced daily by constant flow is a major efficiency factor, therefore, the operation is limited to wells with certain distinct characteristics. Wells should have a high fluid level and high productivity from a limited depth in order to operate most efficiently with this method.

It is very difficult to establish a minimum fluid production figure because of the many factors involved. Depth of operation, available pressure, fluid viscosity, and size of eductor tube are all of major importance. Under average conditions, however, it is possible to establish a broad rule by which wells might be classified as being in the continuous flow category. With two-in. tubing, a minimum of 250 B/D total fluid might be efficiently produced. With two and one-half-inch tubing, a minimum of 400 bbl. and with three-inch tubing, a minimum of 600 bbl.

Generally speaking, quantities under these minimum figures should be produced by intermittent flow. There is, of course, an overlap between the minimum quantity under continuous flow and the maximum quantity under intermittent flow. Where such condition exists, an analysis of local conditions or the operator's preference generally governs the choice of operation selected.

Maximum Fluid Production

The maximum possible fluid production is determined by the ability of the well to produce or the capacity of the eductor tube. When producing through two-inch tubing, a maximum of 1,200 to 1,500 B/D might be expected. Through two and one-half-inch tubing, a maximum of 2,600 to 3,000 bbl should be produced and through three-inch tubing, 4,700 bbl. The estimated maximum production figures above are based on dead lift operations. Where a well has considerable reservoir energy, the possible maximum production may be greater.

The maximum operating depth of an aerating type of flow is a function of available operating pressure and minimum efficient flowing gradient that can be established and maintained in the fluid column. In order to understand this depth limitation, it is necessary that the principle of the method be understood.

Assume a vertical column of fluid 4,000 ft high with an average gradient of .44 psi per foot of height. The column would exert a pressure of 4,000 by .44 or 1,760 psi at its base. If sufficient gas were injected and the column aerated to a point where the average gradient was .20 psi per foot of height, the pressure at the base would be 4,000 by .20 or 800 psi. If the average gradient were .10 per foot of height, the pressure at the base would be 4,000 by .10 or 400 psi.

If an attempt were made to inject gas at the base point in either of the above examples, a pressure in excess of the fluid column base pressure would be required.

The maximum operating depth of this type flow under the existing surface conditions may be expressed in formula as follows: $D = \frac{P - P_s}{G}$

Continued on Page 2, Section 2

The Carthage Gas Field

Reported by W. B. Davis

Mid-Continent Section

Harold M. Harris, petroleum engineer with the U. S. Bureau of Mines at Bartlesville, Okla., presented a paper on the Carthage Gas Field at a recent meeting of the Mid-Continent Section Reservoir Study Group.

At the regular monthly meeting of the Section, December 10, 1951, J. S. Aronofsky of the Magnolia Petroleum Co., Dallas, Tex., presented his paper entitled "Mobility Ratio—Its Influence on Flood Patterns During Water Encroachment." (This paper is published in the Transactions section of this issue.)

Aronofsky preceded the formal presentation of the material in his paper by a discussion of the current concepts of the mechanism of oil displacement by encroaching water. He also discussed the theory of construction and operation of potentiometric models, and compared the conventional forms with the rather specialized form required for this study.

Harris' talk was a summary of the material contained in the Bureau's Report of Investigations No. 4698 published in August of 1950. Harris began by giving a brief description of the field's physical characteristics. The Carthage Field in Panola County, Tex., is the fourth largest gas reserve in the United States. The field is approximately 25 miles long and 20 miles wide. It had 306 producing wells as of July 1, 1948. The three principal gas reservoirs are the Hill, the Upper Pettit and the Lower Pettit of the Rodessa and Sligo formations.

The estimated gas reserves of all three zones amount to about 7.5 trillion cu ft. These reserve estimates are based on volumetric considerations. Harris pointed out that many portions of these reservoirs have such low permeability that the pressures build up very slowly and reservoir pressures since discovery are of questionable accuracy. Therefore, any reserve calculations based on a reservoir performance are also of questionable accuracy. It was for that reason that the reserve figures were based entirely on volumetric considerations.

Natural gas from the Carthage Field is comparatively low in liquid hydrocarbons and the field is classified as "border-line" regarding cycling operations to recover additional liquid hydrocarbons. The gas contains approximately 15 bbl of recoverable liquids per million cubic feet. At the time of the study, the pipeline outlet capacity of the field was about one billion cu ft of gas per day, and five natural gasoline plants and one cycling plant were operating with a total processing capacity of about 350 MMcf/D. Since the survey, both natural gasoline capacity and pipeline outlet capacity have been increased. ★ ★ ★

Corrosion Mitigation in a Colorado Field

Reported by R. D. Ferguson

Wyoming Chapter

At the December dinner meeting of the Wyoming Chapter in Casper, W. L. Giezentanner, division mechanical engineer for the Continental Oil Co., spoke on "Corrosion Mitigation in Wells of the North McCallum Field, Jackson County, Colorado." A discussion period followed the talk, which is presented in condensed form below.

The field, about 65 miles from Laramie, Wyo., has an elevation of about 8,200 ft, and produces from the Dakota sand at a depth of approximately 5,500 ft. It is a condensate reservoir producing about 93½ per cent by weight CO_2. Corrosion was found in the tubing and casing, although the casing was not badly corroded where gas was produced from the tubing only. Surface temperatures are 77°F and BHT 160°F. The rate of corrosion varies from .35 mils at surface to .24 mils at the bottom of the string. Most of the corrosion is found above 2,500 ft. in the tubing. The average life of a string of tubing was 15 months, and casing string two and one-half years.

GEORGE DICKINSON of the Technical Services Group of Shell Oil Co., Houston, spoke before the Southwest Texas Section in Corpus Christi last month on "Geological Aspects of Abnormal Reservoir Pressures in the Gulf Coast Region of Louisiana." The speaker related the occurrence of abnormal pressure to geological factors, and discussed methods of successful drilling through such pressures.

In February, 1947, inhibitor tests were started. The inhibitors used were manganese naphthalate, ammonia hydroxide and Kontol. The first two failed, but Kontol 115 and 118, as a lubricated liquid or in sticks, has been a successful inhibitor.

Giezentanner believes the iron radical from water analysis is an index of corrosion, but that the mild steel coupon inserted in a nipple at the well head connection is a better measurement of the rate of corrosion. In one tubing string the corrosion was about 44 mils per year before injecting two gals per day of Kontol through a lubricator. The corrosion was then reduced to 1.4 mils per year, and now to .15 mils per year.

Examples of caliper surveys on tubing were shown. Plastic coated tubing was also used in some wells successfully. In the Webster well, because of a packer stick, Kontol was dropped at the rate of 11 sticks per week, which reduced corrosion from 240 mils per year to 7 mils per year to .35 mils per year at present. For the field, Kontol costs about $17.00 per well per month, and plastic tubing about $10.00 per well per month. ★ ★ ★

PETROLEUM BRANCH PROGRAM

AIME ANNUAL MEETING IN NEW YORK

Headquarters, Statler Hotel
February 18-21, 1952

LYON F. TERRY
Meeting General Chairman for the Petroleum Branch

SATURDAY, FEBRUARY 16

Meeting of Section Delegates, all AIME Local Sections

SUNDAY, FEBRUARY 17

Meeting of the AIME Board of Directors

2:00 p.m.

MONDAY, FEBRUARY 18

MORNING

Registration

Petroleum Session

10:30 a.m. - 11:30 a.m.

"Natural Gas in the Province of Alberta, Canada," by J. F. Dougherty, Empire Trust Co., New York, N. Y.; Anthony Folger, DeGolyer and MacNaughton, Dallas, Tex.; Howard Lowe, Delhi Oil Corp., Dallas, Tex.; and Joffre Meyer, DeGolyer and MacNaughton, Dallas, Tex.

Presentation and Discussion: 10:30 a.m. - 11:30 a.m.

Exploration activities over the past three years in Alberta, Canada, have placed this area in the forefront of active discoveries of important natural gas reserves. Substantial natural gas reserves have been established with many favorable areas yet to be drilled. Active future exploration undoubtedly will add considerable reserves. A discussion of the general geology of the province, of individual major fields, the possibilities of future reserves, deliverability of gas and the history of utilization of gas in Alberta will be presented.

AIME Welcoming Luncheon — All Institute

For Ladies and Gentlemen

AFTERNOON

Petroleum Session

2:30 p.m. - 5:30 p.m.

"The Stratoflow Process: A Recent Development in Locating Water Entry in Wells," by Ralph E. Hartline and Wilfred H. Tanner, Halliburton Oil Well Cementing Co., Duncan, Okla.

Presentation and Discussion: 2:30 p.m. - 3:15 p.m.

"Significance and Implications of the Growth of the Petroleum Industry," by Stuart E. Buckley, Humble Oil and Refining Co., Houston, Tex.

Presentation and Discussion: 3:15 p.m. - 4:05 p.m.

Production of crude oil in the United States has increased more than thirtyfold since 1900. It has increased tenfold since 1909, and has doubled since 1935. Over a span of years this growth appears to be phenomenal. However, it has not resulted from any sudden spurt, but rather from a modest but steady rate of increase. From 1861 to 1891 the rate of growth averaged 11 per cent a year; from 1904 to 1929 it averaged 10 per cent a year; and since 1933 it has averaged 5 per cent a year. The tremendous increase results from the fact that the percentage increases are compounded. This paper discusses some of the implications of a compounded rate of growth and some of the principal elements that have supported it. The significance of these factors with respect to a continued ample supply is also pointed out.

Panel Discussion on Petroleum Engineering Education, by Members of Petroleum Branch Education Committee.

John C. Calhoun, Jr., Chairman, presiding

Introduction by John C. Calhoun, Jr.

"Elements of Petroleum Engineering Education," by H. G. Botset, University of Pittsburgh, Pittsburgh, Pa.

"Characterizing Features of the Petroleum Engineering Curriculum," by H. H. Power, University of Texas, Austin, Tex.

"Some Current Problems of Petroleum Engineering Educators," by C. F. Weinaug, University of Kansas, Lawrence, Kan.

Presentation and Discussion: 4:05 p.m. - 5:30 p.m.

TUESDAY, FEBRUARY 19

MORNING

Petroleum Session

8:45 a.m. - 11:45 a.m.

"Processing and Recovery of Light Hydrocarbon Liquids in the Field — An Economic Study," by John M. Campbell and Robert N. Maddox, Black, Sivalls and Bryson, Inc., Oklahoma City, Okla.

Presentation and Discussion: 8:45 a.m. - 9:40 a.m.

The light hydrocarbon liquids recoverable from natural gas have become of increasing economic importance with the increased demand for blending stock and LPG products. This demand has encouraged the development of new processing methods in the field in order to increase present recoveries. These new field

recovery methods, although not as efficient as a large gasoline plant, give comparable results. However, in many situations the net economic returns are greater due to a much lower initial and operating expense. A typical gas analysis for those cases where recovery is economically feasible has been used as a basis for the discussion of light hydrocarbon liquid handling problems. The following systems have been investigated: 1. Single and multi-stage separation; 2. Low temperature separation with weathering in the stock tank; 3. Low temperature separation with stabilization. The effect of temperature and pressure on recovery have been developed.

"Capital Formation in the Petroleum Industry," by Frederick G. Coqueron and Joseph E. Pogue, The Chase National Bank, New York, N. Y.

Presentation and Discussion; 9:40 a.m. - 10:40 a.m.

For the past decade, the Petroleum Department of Chase National Bank has conducted a study of financial aspects of the American petroleum industry as exemplified by combined operations of 30 representative oil companies. The American petroleum industry is one of the largest in our national economy, utilizing $33 billion of gross assets and handling a yearly volume of business amounting to $15 billion. Funds required for financing its capital requirements are obtained from two primary sources: internal, from retained cash earnings; and external, from capital markets.

"The Part of the Petroleum Engineer in the Oil Industry Information Program," by Robert E. Featherston, American Petroleum Institute, Tulsa, Okla.

Presentation and Discussion; 10:40 a.m. - 11:20 a.m.

This paper discusses the thinking of many oil men who believe that the responsibility for the conduct and execution of the oil industry's information programs lies entirely with petroleum marketers and company public relations men. It also shows that the petroleum engineer has equally as much at stake in the future of his industry. It points out that he is expected to explain and defend it, and to win for it the public approval and support necessary to stave off increased government regulation and control.

"Salt Water Disposal in the East Texas Field," Movie shown by W. S. Morris, East Texas Salt Water Disposal Co., Kilgore, Tex.

Presentation; 11:20 a.m. - 11:45 a.m.

AFTERNOON

Production Review Session

2:00 p.m. - 5:00 p.m.

WORLD OIL AND GAS DEVELOPMENTS DURING 1951 Presented by the 1951 Production Review Committee

E. W. Berlin, Committee Chairman, Presiding

Domestic Vice-Chairman:
R. B. Gilmore, DeGolyer & MacNaughton

Foreign Vice-Chairman:
Alexander H. Chapman, Arabian American Oil Co.

Committee Members:
A. H. Bell, Illinois Geological Survey
Lawrence W. Chasteen, Union Oil of California
Gordon H. Fisher, Gulf Oil Corp.
Raymond M. Larsen, U. S. Geological Survey
John A. Murphy, Continental Oil Co.
Milton Williams, Humble Oil and Refining Co.
John K. Wright, Jr., Mississippi State Oil and Gas Board

This session consists of brief reviews of world-wide developments and production highlights of 1951. Presentation of papers will be by Committee Members.

EVENING

Petroleum Branch Dinner

Richard W. French, Petroleum Branch Chairman, Presiding

Principal Speaker — John M. Lovejoy, President of Seaboard Oil Co. of Delaware.

Cocktail party in advance. Dress, informal for men, ladies optional. Installation of 1952 Petroleum Branch Officers and presentation of Petroleum Branch Certificate of Service to Stuart E. Buckley.

WEDNESDAY, FEBRUARY 20

MORNING

Open Meeting, Petroleum Branch Executive Committee — 9:00 a.m. - 12:00 m.

EVENING

Annual AIME President's Reception and Banquet

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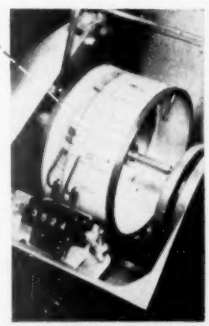

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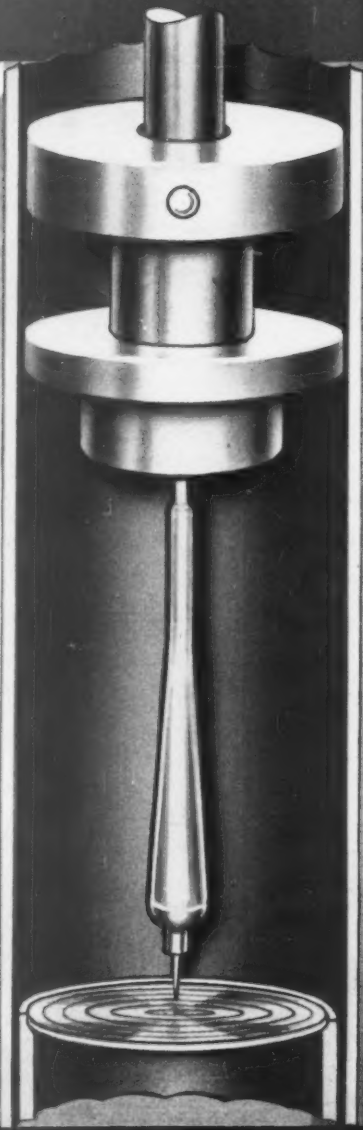

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METHOD FOR DETERMINING WETTABILITY OF RESERVOIR ROCKS

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ABSTRACT

A semiquantitative method for measuring the wettability of reservoir rocks has been developed. These data are needed for reservoir analysis and for interpretation of laboratory displacement studies. The wettability of a core sample is measured by the contact angle for the system oil-water-solid. These contact angles are calculated from the displacement pressure (threshold pressure) obtained by use of the centrifuge, using first oil-water and second air-oil in the same core sample. This method is based on the assumption that the air-oil and oil-water interfaces occupy similar positions in the porous medium when desaturation of the wetting phase is initiated. The assumption is also made that the contact angle for the air-oil-solid system which is close to zero in value does not change appreciably even when the contact angle for the oil-water-solid system experiences marked changes. "Apparent contact angles" for five different solids ranging from 31° to 82° have been determined, and changes in the "apparent contact angle" of a given sample with laboratory use from 33° to 53° have been observed.

INTRODUCTION

Reservoir rocks vary in their wettability,[1,2,3,4] some being preferentially water wet while other are apparently preferentially oil wet. The degree of wettability, in theory, is measured quantitatively by the contact angle for the system solid-oil-water, but in practice this quantity is extremely difficult to determine.[5] The need for obtaining some measure of this quantity has become obvious in recent years as a result of both laboratory and field observations. Several reservoirs such as the Bradford Sand in Pennsylvania and the Wilcox[1] at Oklahoma City are reported to be oil wet. If these reports correctly reflect the true nature of the surface of the rock in the ground, then these reservoirs probably will not perform as predicted on the basis of a water wet rock. In the laboratory many core samples have been observed to be oil wet. These samples, while perhaps not correctly representing the reservoir, have markedly different properties from water wet rock. The location of the phases is different (oil is in contact with rock instead of water), and other quantities such as the connate water, the capillary pressure curve, residual oil, relative permeabilities, and the recovery of oil by water flooding are markedly affected by the value of the contact angle. A further complication observed in the laboratory is the changing of the wettability of a rock specimen with use. Such changes mean that repeat runs on the same core are not the duplicate tests desired, but represent new experiments on a more oil wet material. The changes in surface characteristics are sometimes so rapid that by the time an experiment requiring several days is completed, the results may not be representative of the core as originally described.

The rock material itself (silica, carbonates, etc.), when clean and uncontaminated, is water wet. There seems to be little evidence of the presence of oil wet minerals such as heavy metal sulfides. The oil wetness of reservoir samples, therefore, is believed to be caused by the accumulation of an adsorbed film in which the polar group of a large organic molecule is adsorbed on the surface leaving the organic or hydrocarbon part of the molecule projecting out from the solid. Such a surface is much more readily wet by oil than by water.

These considerations indicate the need for a method which will provide some measure of the wettability (contact angle if possible) for reservoir rock samples. The method should be capable of (1) distinguishing between the wettability of different formations, (2) detecting changes in wettability of a core with use, and (3) measuring the changes in wettability which may be accomplished with cleaning operations, such as the use of sodium silicate for increasing water wettability.[6] A preliminary report on such a method is presented below, not with the idea that this procedure alone will solve the wettability problem, but rather that it may provide encouragement to

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch, AIME, Aug. 9, 1951. Paper presented at the Fall Meeting of the Petroleum Branch in Oklahoma City, Okla., Oct. 3-5, 1951.

others to initiate critical studies on means for determining wettability and for evaluating its importance in reservoir performance.

DESCRIPTION OF METHOD

The wettability of a rock specimen is determined by carrying out two displacement experiments, the first being the displacement of water by oil, the second the displacement of oil by air. The threshold (initial desaturation) pressures determined from these displacement experiments together with the surface tension and interfacial tension values may then be used to calculate a "wettability number," W, defined by the relationship

$$W = \frac{\cos \theta_{o\text{-}w}}{\cos \theta_{g\text{-}o}} = \frac{P_{(o\text{-}w)T}\ \gamma_{g\text{-}o}}{P_{(g\text{-}o)T}\ \gamma_{o\text{-}w}} \quad . \quad . \quad . \quad . \quad (1)$$

which is derived in the following section. An "apparent contact angle" the cosine of which is defined by the relation

$$\cos\ (\theta_{o\text{-}w})\ \text{apparent} = \frac{P_{(o\text{-}w)T}\ \gamma_{g\text{-}o}}{P_{(g\text{-}o)T}\ \gamma_{o\text{-}w}} \quad . \quad . \quad (2)$$

may also be calculated if the assumption is made that the contact angle is zero in the oil for the air-oil-solid system. This calculation yields the receding contact angle measured in the water phase.

THEORETICAL BASIS OF METHOD

In reservoir problems the question of wettability arises when both water and oil are present to compete for a place on the solid surface. The contact angle at each spot in the system where the three phases are present defines the wettability at that spot. The wettability of the reservoir rock may be defined as some average of these contact angles. A solid is considered to be preferentially water wet if the contact angle measured in the water for the oil-water-solid system lies between 0° and 90°. Similarly solids are designated as preferentially oil wet for contact angles (also measured in the water phase) between 90° and 180°. While systems with contact angles less than 90° are called water wet, it is important to note that considerable variation in core properties due to wettability may be observed in this range. The method of measuring wettability discussed herein is largely concerned with the differentiation of cores exhibiting contact angles in this interval. Measuring all of these individual contact angles does not appear to be practical.

It is possible, however, to calculate a "wettability number" and an "apparent contact angle" of the water phase from displacement pressures, air-oil surface tension, and oil-water interfacial tension data if it is assumed (1) that the relationship between the displacement pressure of the wetting phase and the contact angle for a cylindrical capillary,

$$P_{o\text{-}w} = \frac{2\gamma_{o\text{-}w}\ \cos \theta_{o\text{-}w}}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

can be applied to a complex porous system where r is the radius of the capillary, (2) that in a core the same effective radius, r, is applicable in both the air-oil-solid and the oil-water-solid systems at the threshold pressure which represents the condition of initial displacement of the respective wetting phases, and (3) that the apparent contact angle for the air-oil-solid system is close to zero and remains essentially constant with changes in the contact angle for the oil-water-solid system.

The above discussion may be stated in terms of the following equations. For the air-oil-solid system the initial displacement pressure (threshold pressure) is related to the radius, r_t, and the contact angle, $\theta_{g\text{-}o}$, by Equation (4)

$$P_{(g\text{-}o)T} = \frac{2\gamma_{g\text{-}o}\ \cos \theta_{g\text{-}o}}{r_t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Similiarly, in the oil-water-solid system the initial or threshold pressure is given by

$$P_{(o\text{-}w)T} = \frac{2\gamma_{o\text{-}w} \cos \theta_{o\text{-}w}}{r_t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

on the basis of the assumption that the water and the oil in these two cases are similarly located or that r_t may be used in both equations. Dividing Equation (4) by Equation (5) eliminates r_t and gives the ratio

$$\frac{P_{(g\text{-}o)T}}{P_{(o\text{-}w)T}} = \frac{\gamma_{g\text{-}o} \cos \theta_{g\text{-}o}}{\gamma_{o\text{-}w} \cos \theta_{o\text{-}w}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Solving this equation for the ratio of the cosines of the contact angles yields an expression, Equation (7), which is given the name "wettability number," W.

$$W = \frac{\cos \theta_{o\text{-}w}}{\cos \theta_{g\text{-}o}} = \frac{\gamma_{g\text{-}o}\ P_{(o\text{-}w)T}}{\gamma_{o\text{-}w}\ P_{(g\text{-}o)T}} \quad . \quad . \quad . \quad . \quad (7)$$

This expression may be further simplified by the assumption that $\cos \theta_{g\text{-}o}$ is unity. The angle which can be calculated from this assumption, Equation (8), has been named the "apparent contact angle"

$$\cos\ (\theta_{o\text{-}w})\ \text{apparent} = \frac{\gamma_{g\text{-}o}\ P_{(o\text{-}w)T}}{\gamma_{o\text{-}w}\ P_{(g\text{-}o)T}} \quad . \quad . \quad . \quad (8)$$

Thus, two semi-quantitative terms are available to measure the wettability. The first of these is the "wettability number," W, which is calculable using one assumption which makes possible the elimination of r_t; the second is the "apparent contact angle which is obtained from the wettability number as assuming a zero contact angle for the air-oil system. Since neither of these assumptions is strictly correct, the quantities "W" and "apparent contact angle" are considered to be only semi-quantitative. Future work should establish the validity and limitations of this method.

APPARATUS AND PROCEDURE

The wettability number, W, defined by Equation (7), may be readily calculated by the determination of the threshold pressure for air displacing oil and for oil displacing water. These threshold pressures (pressures at which the displacement of the wetting phase is initiated) have been determined rather conveniently by the use of the centrifuge[2] using the first portion of the capillary pressure curve to obtain these values accurately. Surface tension and interfacial tensions are measured with the conventional DuNuoy Tensiometer.

The procedure used in handling of the rock sample is very simple. A core plug cut from the reservoir in question is extracted by any of the conventional schemes which may include the use of carbon tetrachloride, chloroform, acetone, pentane, etc. (If desired, the measurements may also be made on the core plug prior to extraction.) The extracted (or unextracted) core is saturated with water or brine, and the threshold pressure for oil displacing water then determined using the centrifuge or any other convenient method. The same core plug is then cleaned, saturated with oil, and using air as the displacing phase the threshold pressure is then determined for this system. The interfacial tension for the oil-water system and the surface tension for the air-oil system are also measured. With these four measured quantities the wettability number, W, may be calculated by use of Equation (7).

The silicate treatment[3] for increasing the wettability number (making core more water wet) merely involves refluxing

the core in an aqueous solution containig five g per liter of sodium silicate ($Na_2SiO_3 \cdot 9H_2O$).

The observation of higher displacement pressures on cores flushed with water after the above treatment indicates improved water wettability.

RESULTS

"Wettability numbers" and "apparent contact angles" for a number of cores from five different sources measured by the method described above are shown in Table I. These data show that a wide range in these values is possible. The most water wet material in this series according to these measurements is a Devonian Limestone sample with an apparent contact angle of about 31° and a wettability number of 0.854. The substance most nearly oil wet in this series is a Clearfork Limestone with an apparent contact angle of about 82° and a wettability number of 0.138. All cores included in this table had been extracted with chloroform prior to measurement of the wettability except for the Alundum samples which were fired at 1,400°F prior to testing. Also included in this table are the experimental numbers (threshold pressure, surface tension, and interfacial tension) used to calculate the wettability number (Equation 7) and the apparent contact angle (Equation 8).

Changes in the wettability of a core with use in the laboratory is very clearly shown by the data in Table II. The Devonian Limestone cores when originally measured in the laboratory exhibited an "apparent contact angle" of 33° which increased to about 52° when the core containing connate water and tri-isobutylene as the oil phase was allowed to stand in this oil phase for three weeks. Treatment of these cores with silicate, however, largely restored the core to its original condition since the "apparent contact angle" was decreased by this treatment to about 35° which is essentially equal to the original value. Similarly, the wettability of Alundum cores was also observed to change with use. It is interesting to note, however, that even after firing at 1,400°F, the four Alundum cores had appreciably different "apparent contact angles," ranging from about 50° to 70°. These data indicate that Alundum even from the same batch is not a very reproducible material with respect to wettability. After standing in oil, however, this material is remarkably reproducible showing a range in "apparent contact angle" of only 0.6°, the actual values lying between 76.2° and 76.8°.

Table I — Comparison of Wettability Among Core Samples of Different Origins*

Core No.	Description	Initial Desaturation Pressure (Threshold Pressure — psi) air-oil	oil-water	Wettability Number**	Apparent Contact Angle (°)
BTL	Devonian	6.5	6.1	0.84	33
BTN	Limestone	6.8	6.9	0.81	36
BTO		6.25	6.0	0.85	31
BTP		6.4	3.9	0.54	57
1588	Vates	0.66	0.32	0.33	71
1589	Sandstone	0.85	0.3	0.31	71
1590		0.85	0.31	0.32	71
1591		1.00	0.4	0.36	69
1542	Alundum	0.70	0.25	0.32	72
1543	(RA 1139)	0.70	0.28	0.36	69
1544		0.68	0.4	0.52	59
1545	Synthetic	0.67	0.28	0.37	68
1592	Clearfork	0.72	0.24	0.30	73
1593		0.54	0.32	0.53	58
1594	Limestone	1.58	0.32	0.18	80
1595		2.90	0.45	0.14	82
1620	Tensleep Sand	0.86	0.21	0.22	78
1621		0.86	0.21	0.22	78
1622		0.68	0.12	0.16	81
1623		0.86	0.27	0.28	74

*Routine Extraction with Chloroform Preceded Wettability Tests Except Alundum Which Had Been Regenerated at 1400°F for Three Hours.
**Air-Oil Surface Tension = 24.9 Dynes/cm. Oil-Water Interfacial Tension = 28.0.

Table II — Changes in Wettability of Cores with Use in Laboratory

Core No.	Core Description	Treatment Prior to Wettability Measurement	Wettability Number	Apparent Contact Angle
BTL	Devonian	Routine Extraction with Chloroform	0.84	33
BTN			0.81	36
BTO	Limestone		0.85	31
BTP			0.54	57
BTL	Devonian	Cores, at Connate Water, were Stored in Oil for Three Weeks	0.60	53
BTN			0.61	52
PTO	Limestone		—	—
BTP			0.60	53
BTL	Devonian	Cores Refluxed with ¼% Sodium Silicate ($Na_2SiO_3 \cdot 9H_2O$) for 24 Hours, Followed by Brine Extraction	0.79	37
BTN			0.76	41
BTO	Limestone		0.89	28
BTP			0.80	37
1542	Alundum	Renegerated at 1400°F	0.32	72
1543	(RA1139)		0.36	69
1544			0.52	59
1545			0.37	68
1542	Alundum	Above Cores — Re-treated by Regeneration at 1400°F	0.76	50
1543	(RA1139)		0.33	71
1544			0.39	67
1545			0.35	70
1542	Alundum	Saturated with and Stored in Oil for 12 Hours Then Dried	0.23	77
1543	(RA1139)		0.23	77
1544			0.24	76
1545			0.24	76

Table III — Comparison of Threshold Pressures for the Air-Oil-Devonian Limestone System Before and After a Series of Laboratory Treatments

Core Number	Threshold Pressures (psi) Before	After	% Change
BTL	6.5	6.6	+ 1.5
BTN	6.8	6.7	− 1.5
BTO	6.25	7.1	+ 13.5
BTP	6.4	6.6	+ 3.2
	Avg. = 6.5	Avg. = 6.75	

The uniformity in the wettability of the Alundum samples after exposure to oil, coupled with similar behavior of the Devonian Limestone samples (see Table II) suggests a possible wettability equilibrium condition in the reservoir which is partially oil-wet. Obviously much more extensive studies under carefully controlled conditions must be completed before this possibility can be evaluated reliably.

Results of tests of the basic assumption that the wettability of the air-oil-solid system does not change with core treatment are presented in Table III in which comparison of the air-oil displacement pressures for Devonian Limestone plugs before and after a series of laboratory treatments is made. These data indicate a relatively minor change in the average value of the threshold pressure from 6.5 psi to 6.75 psi, most of this change arising from a large difference in one core. If the results from this core were not considered, the change in the average threshold pressure would have been merely from 6.57 psi to 6.63 psi. Considering the processing to which the cores were subjected (made partially oil wet by storage in oil, dried, saturated with water, oil driven, vacuum distilled, saturated and refluxed with sodium silicate solution, extracted with brine, oil driven, vacuum distilled, saturated with oil, and air driven) these results offer some support for the assumption that the contact angle in the air-oil-solid system is relatively constant.

It is interesting to note that rough tests such as the behavior of oil and water droplets on the surface of the solid are in complete qualitative agreement with the more quantitative results obtained by the method described above. Thus, dry solids with small "apparent contact angles" readily imbibe water droplets as well as oil, while only oil is observed to be readily imbibed by solids which show a large "apparent contact angle." It should be clearly understood, however, that these qualitative tests are unable to differentiate between solids which have appreciable differences in the "apparent contact angle" such as 33° *vs* 55°. It is in the differentiation

between such materials that the new method offers considerable encouragement. With such precision not only can slight differences between similar cores be distinguished, but changes in a specific specimen can be followed, and the efficiency of methods for modifying the wettability can be measured.

LIST OF NOMENCLATURE

W = Wettability number — increases toward unity as system becomes more water wet
$\theta_{o,w}$ = Contact angle in water for oil-water-solid system
$\theta_{a,o}$ = Contact angle in oil for air-oil-solid system
$P_{(o,w)T}$ = Three-fold pressure for displacement of water by oil
$P_{(a,o)T}$ = Threshold pressure for displacement of oil by air
$\gamma_{a,o}$ = Surface tension (dynes/cm) for oil-air system
$\gamma_{o,w}$ = Interfacial tension (dynes/cm) for oil-water system

ACKNOWLEDGMENT

The authors gratefully acknowledge the able assistance of Mrs. Wesley Marshall, who performed the experimental work reported in this paper.

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DISCUSSION

By S. R. Faris, Member AIME, and J. W. Whalen, Magnolia Petroleum Co., Dallas, Tex.

The authors have presented a subject which is of great importance and interest to the industry and this paper should stimulate interest and further work on this subject.

Wetting phenomena are intimately related to the surface of the porous medium and may be expected to vary from point to point on this surface because of the chemical nature of the surface and its physical roughness. Wettability characteristics of chemically homogeneous surfaces have been estimated from displacement pressure measurements by a number of investigators.[1] The nature of the surface forces existing in a reservoir rock material, however, should be described in terms of an average value resulting from consideration of the entire surface. The authors, in utilizing the air-oil and oil-water displacement pressures to calculate a "wettability number," are considering only the largest of capillaries comprising the porous medium. In addition the "apparent contact angle," in terms of which the "wettability number" is defined, is considered at only one point on the surface of these capillaries. Wettability characteristics based on an infinitesimal fraction of the surface exposed to flow clearly are not representative of the entire porous matrix.

The extension of this method to capillaries of smaller radii by use of the complete air-oil and oil-water capillary pressure curves, at points of equivalent wetting-phase saturation, is severely limited by the assumption of equivalent capillary radii. It would be interesting, however, to compare the "apparent contact angles" obtained in this manner to those obtained at the conditions of initial displacement pressure.

The authors have mentioned the relationship of the "apparent contact angle" to the receding contact angle. Adam[2] has pointed out that although wetting-phase displacement pressures should indicate receding contact angles and imbibition pressures advancing contact angles, variations shown by different liquids on silica do not indicate that the relationship is a well defined one. The variations noted by Adam may be an additional reason for questioning the assumption of equivalent capillary radii.

Although the authors indicate the semi-quantitative nature of the work described in the paper, and state that the chief utility of their method is to follow apparent changes in the wettability character of the solid surface, it should be emphasized that the concept of wettability as defined by the "apparent contact angle" is a greatly over-simplified one and that the significance of contact angle as applied to reservoir material is poorly, if at all, understood.

The "apparent contact angle" measurements have been obtained for the system under static conditions and from this standpoint their significance may be largely artificial if used to define the wettability characteristics of the rock under dynamic conditions where knowledge of the interfacial character (wetting phase advancing or receding) is necessary. In addition, Adam[3] has shown that the geometry of the capillary greatly influences the nature of the interface advance and attendant displacement pressure. It is hoped that the interest created by the static "apparent contact angle" study of the authors will result in the extension of wettability studies to dynamic systems and in better understanding of the complex problems involved in such systems.

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AUTHOR'S REPLY TO MESSRS. FARIS AND WHALEN

The comments of S. R. Faris and J. W. Whalen may be looked on as a continuation of the discussion in the paper. We are in essential agreement with what is said and insofar as the suggested measurement of "apparent contact angles" as a function of saturation, several such determinations were made early in the study and more work is planned. Our intent in presenting this paper was to set forth the method and assumptions clearly and simply. For this reason discussion of complicating factors was deliberately left out of the paper. The above discussion supplies supplementary information which aids in relating the proposed method to other problems within the broad scope of the wettability problem.

RADIAL FILTRATION OF DRILLING MUD

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ABSTRACT

A laboratory investigation has been made of the effects of mud hydraulics upon the formation and erosion of mud filter cakes. The tests were conducted to simulate drilling conditions as nearly as possible.

The formation of mud filter cake in a drilling well does not proceed at a uniform and unbroken rate. Instead, the rate of cake accumulation depends upon whether or not the mud is being circulated. If the mud column is quiescent, filter cake formation is a smooth function of the filtration characteristics of the system. If the mud is being circulated filter cake formation depends not only upon the filtration characteristics of the mud but also upon the erosive action of the flowing mud column.

Filter cakes formed during continuous mud circulation were observed to reach an equilibrium thickness after several hours' circulation. Mud circulation was maintained at a constant volumetric rate throughout each experiment. The fluid velocity at equilibrium cake thickness was dependent upon the thickness of the filter cake. Muds having exceptionally high water loss deposited thick filter cakes in spite of very high eroding velocities. The muds having good filtration characteristics deposited thin filter cakes at equilibrium circulating velocities well within the range of those used in a drilling well.

It was observed that filter cakes deposited during stagnant filtration were quite difficult to erode by mud circulation. The rate of erosion computed from the rate of filtrate accumulation after equilibrium cake thickness had been reached was in reasonable agreement with the rate of erosion obtained by direct observation. Continuous mud circulation usually caused the permeability of the filter cake to decrease with time.

INTRODUCTION

Many of the difficulties encountered during the drilling of a well have been attributed to the loss of water from the mud and the attendant deposition of solids upon the walls of the hole. Past experience has shown that a reduction of the filtration rate of the drilling fluid eliminates or greatly reduces these difficulties. Definite filtration requirements, however, are hard to establish for a given set of conditions. This is due, in part, to the fact that the usual filtration test performed upon mud does not simulate well conditions as closely as desirable.

The filtration characteristics of a mud are customarily determined by means of the standard low-pressure API wall-building tester.[1] In this instrument a filter cake is deposited upon a horizontal bed under a pressure differential of 100 psi. The mud is quiescent during the filtration period. In actual practice, mud filtration occurs within a well under quite different conditions. One of the major differences is that mud flows upward across the filter bed as the filter cake forms. This undoubtedly produces a change in the filter cake which cannot be reflected in the results of the API test.

The laboratory work described in this paper had as its primary objective a better understanding of the influence of mud circulation upon the thickness and characteristics of the filter cakes deposited under conditions similar to those existing in a drilling well.

ANALYSIS OF PROBLEM

Once a permeable formation is penetrated by the bit, filtrate from the mud flows into the formation. The mud solids plaster against the walls of the hole, forming a filter cake. If the mud column is stagnant, that is, if it is not being circulated, the filter cake will increase in thickness until the hole is filled. Prior to the time that the hole is filled, the thickness of filter cake existing at any given time will be a function of the filtration characteristics of the mud, the temperature, and the pressure differential. The effects of these variables have been investigated in the past for both flat bed filtration[2,3] and for radial filtration.[4]

When the mud is circulated in a hole in which a filter cake is being deposited, some of the solids that would ordinarily deposit in the filter cake will be carried away by the eroding action of the mud. This will limit filter cake thickness. Some work has been done to determine the effect of flow upon the filtration rate in a circulating mud system[4] but little work has been done upon the factors which determine the filter cake thickness existing in a circulating system.

On first sight it would appear that the major factors controlling filter cake formation in a circulating system should be:

1. The rate of deposition of solids from the mud.
2. The erosive force that the flowing mud exerts upon the filter cake.
3. The erodability of the filter cake.
4. Any change in filter cake characteristics attributable to the scouring action of the mud.

The rate at which solids are deposited from the mud will be controlled to a large degree by the filtration characteristics of the mud, the pressure differential, the temperature under

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch August 9, 1951. Paper presented at the Petroleum Branch Fall Meeting in Oklahoma City, Okla., Oct. 3-5, 1951.

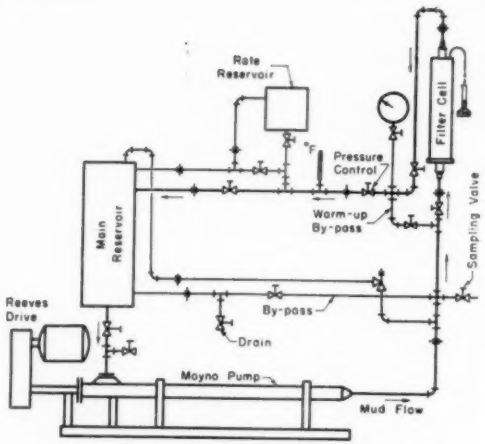

FIG. 1 — DIAGRAM OF RADIAL FILTRATION APPARATUS.

which filtration is taking place, and the thickness of the filter cake already in place.

The erosive action of the circulating fluid should be dependent upon the circulation velocity, the fluid properties, and the type of flow existing in the fluid column, *i.e.*, whether turbulent or viscous.

It seems reasonable to expect some filter cakes to be more difficult to erode than others. Thus, although two muds may have identical filtration rates and filter cake thicknesses as determined by the API test, the filter cakes deposited from the two muds may not offer the same resistance to erosion.

Although the major factors controlling the thickness of a filter cake deposited during circulation should be those mentioned above, the further possibility exists that some classification of the filter cake solids may take place while the cake is being formed. Solids having certain properties may be concentrated in the filter cake. Such an effect might be expected to alter the filter cakes sufficiently to affect their thickness somewhat.

The experimental work described in the following sections was designed to investigate the effects of the foregoing factors on filter cake formation during mud flow.

EXPERIMENTAL PROCEDURE

Apparatus

The laboratory apparatus was designed to simulate as closely as possible the conditions under which filtration occurs in a well. A sketch of the equipment is shown in Fig. 1. The equipment consists essentially of a mud reservoir, a circulating pump, and a radial filter cell. Provisions were made for control of the pressure differential across the filter bed, the circulating volume, and the mud temperature. The filter cell consisted of either (1) a hollow sand cylinder, prepared by consolidation of screened sand with phenol-formaldehyde resin, or (2) a hollow cylinder of permeable sintered brass. The details of the sand filter cell are shown in Fig. 2. The sand column had an inside diameter of 2 in., an outside diameter of 4 in., and was 24 in. in length. The sintered brass filter cell was similar to that using consolidated sand as a filter bed, except that all its dimensions were roughly one-half those of the sand.

Technique

In most of the experiments the pressure differential across the filter cake was kept at 350 psi, and the temperature at about 110°F. It was felt that these conditions were fairly representative of conditions in a well.

Two techniques of investigation were used. These were:

1. Determination of equilibrium thickness of filter cake deposited during continuous mud flow. In the use of this technique mud was circulated through a by-pass until the temperature reached about 110°F. Mud was then allowed to flow through the filter cell at a predetermined volumetric rate, and the by-pass was closed. The thickness of filter cake deposited was measured from time to time. To do this it was necessary to interrupt the run, open the filter cell and gauge the size of the hole open to mud flow. The test was continued until the thickness of the filter cake ceased to increase. A record was kept of the volume of filtrate which had accumulated at various elapsed times.

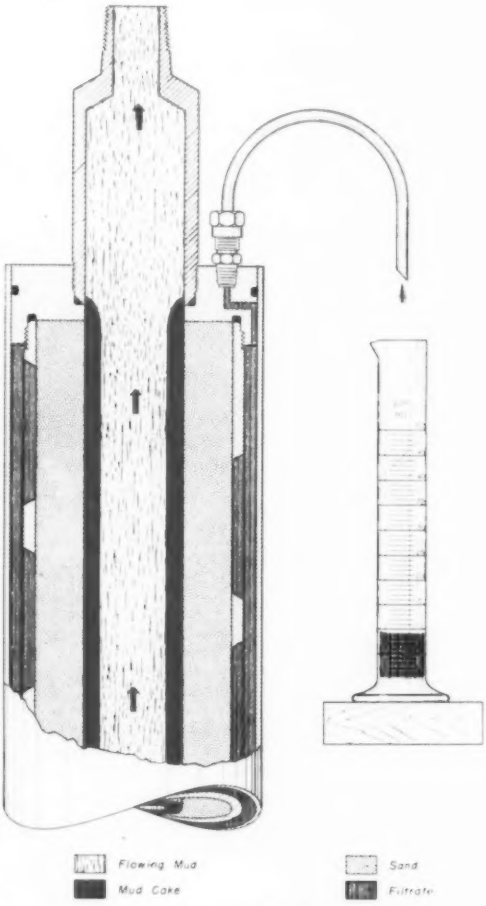

FIG. 2 — RADIAL FILTER CELL.

2. Determination of the thickness of filter cake deposited under static conditions and then eroded by mud flow. In the use of this technique mud was allowed to filter through the filter cell without flowing axially through it. Filtration was allowed to continue at a predetermined pressure and temperature until a very thick filter cake was deposited. Mud was then flowed through the cell at a constant volumetric rate until the filter cake eroded to a constant thickness.

Some auxiliary measurements were made in order to determine the effects of viscosity and velocity upon filter cake erosion. In general, these procedures were similar to those described above.

Muds Used

The muds used in these tests were all prepared in the laboratory. Properties and compositions of the muds are shown in Table I. The muds covered a range of viscosity from 2 to 85 cp (Stormer at 600 RPM) and a filtration range of 7 to 148 cu cm API. The table gives the filtration rates of the muds at both 100 psi and 350 psi. In the discussion to follow the results of the API test (100 psi) will be used as it is a standard test and offers no particular disadvantage to the interpretation of the data.

RESULTS

Effect of Filtration Rate Upon Equilibrium Thickness of Cake

Experiments conducted by depositing a filter cake during continuous mud circulation showed that, in general, the higher the filtration rate of a mud, the thicker was the equilibrium filter cake and the higher was the eroding velocity necessary to stop further formation of filter cake.

Typical results are illustrated in Table II. All of these data were obtained by use of the sand filter cylinder. As shown in Table II, a mud whose API filtration rate was 148 cu cm in 30 minutes caused a filter cake 21/32 in. thick to form before an equilibrium thickness was reached. The velocity required to prevent further formation of filter cake was 530 ft per min. As the API filtration rate was decreased, the filter cake thickness and the velocity required to stop further formation of filter cake decreased, so that for a mud having a filter loss of 19 cu cm in 30 minutes a circulating velocity of 125 ft per min permitted only a 1/32 in. cake to form. An 8 cu cm mud formed a cake 3/32 in. thick while exposed to a velocity of only 48 ft per min. The filtration curve for this particular run is shown in Fig. 3. This is a typical curve. The rate of accumulation of filtrate decreased although the filter cake thickness reached a constant value. For this reason the rate of accumulation of filtrate could not be used as an indication of filter cake thickness but actual measurements had to be made.

Table I — Properties of Muds Used in Radial Filtration Experiments

Mud Designation	Filtration Rate, API at 100 psi cu cm in 30 min	Filtration Rate, API at 350 psi* cu cm in 30 min	Viscosity Stormer (at 600 RPM) cp	Composition
F	19	21	3	Aquagel, lime, kembreak, caustic, quebracho
G	85	151	2	Zeogel, baroid, lime, kembreak, caustic, quebracho
I	148	217	2	Zeogel, baroid, lime, kembreak, caustic, quebracho
J	35	53	3	Baroco, lime, kembreak, caustic, quebracho
K	10	14	5	El Paso clay, caustic, quebracho
K-a	4.6	—	85	El Paso clay, aquagel, caustic, quebracho
P-a	8	11	2	Baroco, baroid, caustic, quebracho
R	10	14	4	Baroco, lime, caustic, quebracho
S	136	181	2	Zeogel, kaolin, salt, caustic, quebracho
S-a	88	147	70	Zeogel, kaolin, salt, caustic, quebracho
T	49	56	5	Baroco, kaolin, salt, starch
W	7.0	9	3	Baroco, kaolin, caustic, carbonox, lime, diesel oil

*Test at 350 psi run on Baroid HP Tester and results corrected to filter area of LP-API Wall Building Tester.

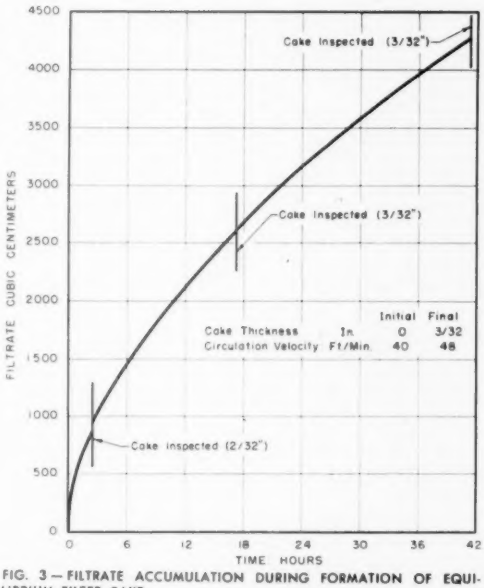

FIG. 3 — FILTRATE ACCUMULATION DURING FORMATION OF EQUILIBRIUM FILTER CAKE.

The filtration rate of a mud had little or no effect on the cake thickness when cakes deposited under static conditions were subjected to several hours' erosion by mud flow. All filter cakes deposited without circulation were extremely difficult to erode by mud flow, and the cake thicknesses determined by this technique were appreciably greater than the equilibrium thicknesses determined by allowing the cakes to build up under continuous mud flow. Table III shows the thickness of each of several filter cakes that were formed in the absence of circulation and then subjected to erosion by mud flow.

The data indicate that a water loss of about 20 cu cm API would be sufficiently low to insure thin filter cakes in a drilling well so long as circulation is continuous. However, during the course of drilling a well mud circulation may be stopped for several reasons, *e.g.*, to run casing, change bits, etc. Once circulation is stopped and a thick filter cake is formed in a hole, the cake will be extremely difficult to erode by circulation alone. Thus, as far as filter cake formation is concerned the lower limits of water loss requirements are probably set by the filter cake that will form when the mud is not being circulated rather than by the filter cake that will form during circulation.

Effect of Viscosity Upon Erosion Rate

Mud viscosity appears to affect erosion only insofar as it controls the type of flow existing in the circulating fluid, *i.e.*, whether it be turbulent or viscous. Experiments undertaken

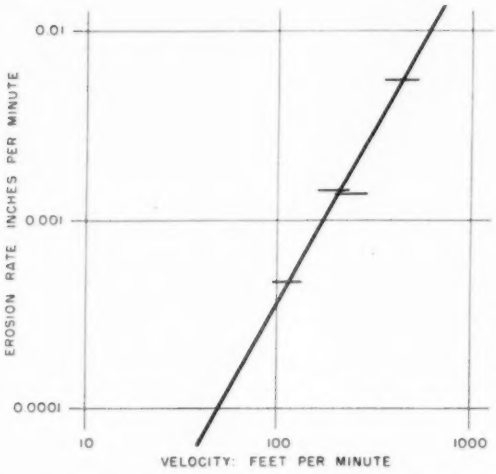

FIG. 4 — EFFECT OF CIRCULATION VELOCITY ON EROSION RATE (TURBULENT FLOW).

to determine the effects of very high viscosities upon erosion rate failed to show any significant change in erosion rate except as mentioned. One experiment designed to determine the effect of viscosity upon erosion was conducted by observing the effects of mud circulation upon the erosion of a pre-formed filter cake. To establish a basis for comparison, a low viscosity mud was circulated past the filter cake. The erosion that resulted was observed. This was followed by the same mud but treated to a very high viscosity. The erosion was again observed. Finally a very thin fluid which resembled the mud filtrate in chemical composition was circulated through the filter cylinder. The effect of mud viscosity upon the erosion of pre-formed filter cakes is presented in the upper part of Table IV. The thick, pre-formed filter cake was eroded by the low viscosity mud until the circulation velocity had dropped from 1,200 ft per min to 430 ft per min. Circulation of the very high viscosity mud caused no further change in cake thickness, and the circulation velocity remained at 430 ft per min. Circulation of the thin fluid produced some additional erosion, and the velocity dropped to about 200 ft per min during the run.

In a second series of experiments a low viscosity mud was circulated in turbulent flow until equilibrium had been reached in cake thickness and circulation velocity. The mud viscosity was increased by the addition of clay and the run repeated. This time the mud was circulated in viscous flow. The effects of mud viscosity upon the thickness of filter cakes deposited during mud flow are also presented in Table IV. Of the two muds, the mud of lower viscosity had the higher API filtration rate, but it deposited a thinner filter cake than did the mud of higher viscosity. This difference is further emphasized by the very high flow velocities which existed in the viscous mud at the end of the experiment.

The tests described indicate that a fluid flowing in turbulent flow will be considerably more erosive than will a fluid flowing in viscous flow. This might be expected from a consideration of the difference in the two types of flow. Turbulent flow designates a condition where the flow stream contains many more or less violent eddies. The walls of the flow channel are scoured by currents at oblique angles to the direction of flow. In contrast viscous or laminar flow denotes a flow condition where the individual fluid particles are all moving in the direction of flow. The walls of the flow channel are exposed to a constant shear stress but to much less scouring.

From the data it appears that changes in mud viscosity will not appreciably affect filter cake erosion rates as long as the changes do not cause a switch between turbulent and viscous flow. It appears that erosion rates are higher and filter cakes are thinner when the filter cakes are exposed to turbulent flow than when they are exposed to viscous flow.

Effect of Velocity Upon Erosion Rate

Some pre-formed filter cakes were eroded by circulating a thin clear fluid past them. The eroding liquid was made to resemble the filtrate from the muds that were used to deposit the filter cakes. Observations were made of the effect of circulation velocity upon erosion rates. This technique allowed direct observation of filter cake erosion in the absence of filter cake deposition. The experiment was conducted at one circulation velocity until significant erosion had occurred. The extent of erosion was measured, and after deposition of a fresh filter cake the run was repeated at another velocity. A pressure differential of 13 psi was held across the filter cake during each erosion test. In all the tests the circulating fluid was flowing in turbulent flow.

It was found that a fluid flowing in turbulent flow would erode a filter cake at a rate proportional to the square of the circulation velocity. These data are illustrated in Fig. 4. Probably the most significant fact illustrated by the data is the slowness with which filter cake erosion occurs. At normal circulation velocities filter cake erosion was in the order of 1/20 in. per hour.

A further check was made upon filter cake erosion by an analysis of the equilibrium data obtained during continuous circulation and filter cake formation. To do this it was assumed that at filter cake equilibrium the rate of deposition of solids was just equal to the rate of erosion of the filter cake. The measured rate of filtrate accumulation and the amount of filter cake deposited per unit volume of filtrate were used to calculate the rate of deposition of solids. The volume of filter cake deposited per volume of filtrate was measured in an auxiliary experiment. The calculated rate of filter cake erosion was plotted against circulation velocity. These data are shown in Fig. 5. The erosion rate increases with circulation velocity, being approximately proportional to the square of the circulation velocity. It can be seen that the erosion rates obtained from the calculations are reasonably close to erosion rates obtained by direct observation. The differences in the erosion rates obtained at any given velocity were probably due to differences in erodability of the various filter cakes.

Erodability

Some muds deposit filter cakes that are harder to erode than others. Direct measurements were made of the erodability of pre-formed filter cakes which were exposed to a circulation velocity of 300 ft per min. The circulating fluid was flowing

Table II — Effect of Filtration Rate on Equilibrium Thickness of Filter Cake

Mud Used	Cake Eroding During Deposition — Turbulent Flow. Consolidated sand filter cylinder. Pressure differential — 350 psi. Filtration Rate LP-API cu cm in 30 min	Filter Cake Thickness in.	Equilibrium Velocity ft/min
P-s	8	3/32	48
R	10	6/32	72
F	19	1/32*	125*
G	85	19/32	220
I	148	21/32	530

*Circulation velocity increased by use of a mandrel.

in turbulent flow and was similar in composition to the filtrate from the muds which formed the cakes. A tenfold difference between the erosion rates was observed for the two muds tested. A caustic-quebracho-clay-barytes mud (API water loss — 8.0 cu cm) deposited a filter cake that would erode at 3×10^{-3} in. per min, whereas a clay-fresh-water mud (API water loss — 52 cu cm) deposited a filter cake that would erode at a rate of only 3×10^{-4} in. per min.

The erosion rates given above are quite low, but it should be noted that once an appreciable filter cake has formed from a mud having a moderate water loss, filter cake accumulation proceeds at a very low rate. Take, for example, the formation of a filter cake from a mud having a water loss of 10 cu cm API. On the assumption that 0.4 cu cm of filter cake will be deposited for every 1.0 cu cm of filtrate passing through the cake, it was computed that by the time the filter cake has reached a thickness of 4/32 in., the rate of formation of filter cake will be of the order of 1.6×10^{-4} in. per min.

Filter Cake Characteristics

Several investigators[5] have found that, below a certain critical size, large particles are washed from the bottom of a stream or river with greater ease than are small ones. The critical size has been set near 0.5 mm. That is, for particles below this critical size, larger particles are moved along the bottom of a channel, while the small ones remain in place. With the exception of cuttings, nearly all the material in a drilling mud is below the critical size. This suggests the possibility of a size classification within a filter cake. Several runs were made in the radial filter to check this possibility. It appeared that size classification was the cause of a continual reduction in filter cake permeability during a circulation period.

A filter cake deposited in a quiescent filter cell showed little change in permeability during a long filtration period. Filter cakes deposited during continuous circulation would gradually decrease in permeability as long as the experiment continued. This was evidenced by a continual decrease in filtration rate after the filter cake had reached a constant thickness. During one run, which continued for 3.7 days, the permeability of the filter cake dropped from 6.0×10^{-4} md to 2.0×10^{-4} md.

CONCLUSIONS

1. As far as filter cake thickness is concerned, the lower limits of water loss requirements are probably set by the amount of filter cake that will form during the time the drilling mud is not being circulated rather than by the thickness of filter cake that will form during circulation.
2. In a mud stream that is being circulated continuously, thin filter cakes are formed if the API water loss of the mud is maintained near 20 cu cm or less.
3. A thick filter cake formed during a period of no circulation is very hard to wash away by mud circulation.
4. Much thicker filter cakes are to be expected with the mud flowing in viscous rather than in turbulent flow.

Table III — Filter Cake Thickness After Prolonged Erosion

	Cake Deposited, Then Eroded — Turbulent Flow		
Mud Used	Filtration Rate LP-API cu cm in 30 min	Filter Cake Thickness in.	Final Circulation Velocity ft/min
R	10	23/32	430
J	35	21/32	420
I	148	25/32	920

Table IV — Effect of Viscosity on Filter Cake Erosion

	Cake deposited, then eroded			
Mud Used	Filtration Rate LP-API cu cm in 30 min	Filter Cake Thickness in.	Viscosity Stormer (600 RPM) cp	Equilibrium Velocity ft/min	Type of Flow in Core
Consolidated sand filter cylinder — pressure differential 350 psi					
K	10	23/32*	5	430	Turbulent
K-a	4.6	23/32	85	>430	Viscous
**		18/32	1	≤200	Turbulent
Sintered brass filter cylinder — pressure differential 350 psi Cake eroding during deposition					
S	136	4.5/32	2	545	Turbulent
S-a	88	7/32	70	1,280	Viscous

*Prior to erosion the cake was 27/32-in. thick.
**Caustic-quebracho solution.

5. In turbulent flow, erosion of filter cake increases approximately with the square of the circulation velocity.
6. Continuous mud circulation past a filter cake nearly always decreases the permeability of the filter cake.

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ACKNOWLEDGMENT

The author wishes to thank the Humble Oil and Refining Co. for permission to publish this paper, and to express his appreciation for the help given by his associates in obtaining a large part of the data.

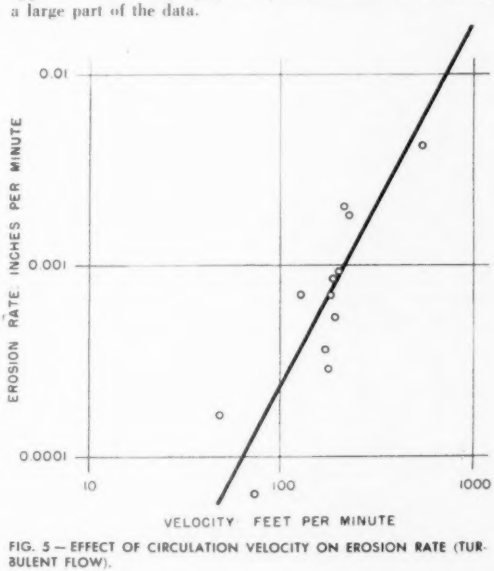

FIG. 5 — EFFECT OF CIRCULATION VELOCITY ON EROSION RATE (TURBULENT FLOW).

DISCUSSION

By O. W. Van Dyke, Magnet Cove Barium Corp., Houston, Tex., Member AIME

Prokop has presented some very interesting facts about mud filtration, cake deposition, and cake erosion by fluid circulation. The radial filtration apparatus and the procedure described indicate some of the complexities of this problem and the large amount of work that is required to study the filtration performance of a mud under laboratory conditions that are designed to simulate hole conditions. The physical properties of the muds used in these experiments do not approximate field drilling fluids as closely as would be desired. It is hoped that Prokop will continue this work and in the future include results obtained using a variety of types of muds taken from drilling wells.

It is evident that there are factors, other than those considered in this paper, which affect filtration and cake deposition in a drilling well, otherwise it would not be possible to work in holes with as much freedom from filter cake trouble as we do. It is probable that the rubbing action of the bit and drill pipe decreases the permeability and thickness of the filter cake deposited on permeable zones in a hole. Prokop observed a continued decrease in the filtration rate after the cake thickness had reached an equilibrium between deposition and erosion. The explanation offered of particle size classification in the filter cake seems very logical. If continued circulation brings about a particle size classification in the filter cake which reduces the permeability, it seems reasonable to expect that the rubbing of the bit and drill pipe may bring about a rearrangement of the particles in a filter cake which influences its permeability.

I would like to suggest that the mechanical action of the bit and drill pipe upon the filter cake be considered in mud filtration studies that are to simulate conditions of a drilling well.

AUTHOR'S REPLY TO MR. VAN DYKE

Van Dyke suggests that the muds used in the experiments did not approximate field muds as closely as desirable. The muds were all laboratory muds designed for stability of properties and made to cover a rather wide range in filtration rates. When an effort was made to use field muds, their properties were observed to change rapidly because of the unusual amount of agitation to which a mud was subjected in the experimental equipment.

The mechanical action of the drill pipe and the bit were not studied. This was because it seemed advisable to find the effects of mud hydraulics upon filter cake formation in a system that was not any more complicated than necessary. No doubt drill pipe rotation and the action of the bit influence filter cake characteristics. But this was considered to be a separate problem.

DISCUSSION

By H. T. Byck and H. C. H. Darley, E. and P. Research Division, Shell Oil Co., Houston, Tex.

We were particularly interested in this paper because it gave experimental evidence on a question in which we have long been interested; namely, how soon does the filter cake on the walls of the hole reach an equilibrium thickness. The point is important because a condition where filtration proceeds without increasing the cake thickness is essentially different from that prevailing in the API test so that, as Prokop has pointed out, the test will not be a true measure of the performance to be expected in the well. When the cake thickness is constant, the water loss to the formation will be proportional, not to the API test water loss, but to the permeability of the filter cake and the equilibrium thickness it assumes in the well. Fortunately, the former can be calculated approximately from the data of the API test. It can be shown from D'Arcy's Law that the permeability of the cake in millidarcies is equal to the product of the filtrate volume in cubic centimeters, the cake thickness in millimeters and a constant which is equal to 7.18×10^{-3} at 30°C. We would emphasize that cake permeability is not proportional to the test water loss, the difference being that the latter varies with the concentration of solids in the mud, whereas the cake permeability does not.

So two unknowns remain: how soon does the cake reach equilibrium thickness, and what is this equilibrium thickness. Prokop has provided some interesting and valuable data on these points, but we feel that one important factor has been omitted, doubtless because it would be extremely difficult to duplicate in the laboratory; that is, the eccentric rotation of the drill pipe wearing down the cake. There can be no doubt that a long flexible shaft such as the drill pipe must continually sweep the sides of the hole, and in fact we have good evidence of this in the wear on tool joint protectors and the inside of casing strings. This may well be one of the principal factors affecting the equilibrium thickness of the cake, and may upset Prokop's conclusion that the cake laid down under static conditions will retain its thickness after drilling is resumed. Our own feeling on the question of the cake thickness in the well is that this will be determined not so much by the properties of the mud as by the mechanics of drilling, *i.e.*, the circulation rate and other factors mentioned by Prokop, plus the action of the drill pipe, and whether or not the hole has been drilled to gauge, etc. If this is so, then the only significant property of the mud governing water loss to the formation for a condition of constant cake thickness is the permeability of the filter cake.

To sum up, conditions in the hole are so complicated that it appears unlikely that a routine test can be devised to yield data directly proportional to the performance of mud in the well. However, we ought to recognize that two general conditions occur in the well: (1) the filter cake increases as filtration proceeds and (2) the thickness remains constant but water loss continues through it. The API water loss is the best criterion for the former, the cake permeability for the latter.

AUTHOR'S REPLY TO MESSRS. BYCK AND DARLEY

Byck and Darley are correct in emphasizing the influence of cake permeability upon the amount of filtrate that will penetrate a formation once a constant filter cake thickness has been reached. The permeability of a filter cake is, however, a function of several variables. One of the most influential is the pressure differential across the cake. When a single measurement of cake permeability is presented, the pressure at which the measurement was made should be specified. The permeabilities mentioned in the paper were measured while there was a pressure differential of 350 psi across the cake. The formula presented in the discussion appears to be applicable to the standard API test. This test is made at 100 psi.

References 2 and 4 of the paper include a discussion of the effect of filtration pressure upon filter cake permeability.

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VOLUMETRIC BEHAVIOR OF CONDENSATE AND GAS FROM A LOUISIANA FIELD—II

B. H. SAGE, MEMBER AIME, AND H. H. REAMER, CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIF.

ABSTRACT

The formation volume and the relative volume of the liquid phase of mixtures of condensate and gas from five different parts of a field in the Louisiana area have been established experimentally. These studies included gas-condensate ratios as high as 25,000 cu ft/bbl at pressures up to 5,000 psi. The gravities of the tank condensates were between 53.9° and 63.9° API.

The compositions of the condensate and gas samples investigated are presented in tabular form. The formation volume, the relative volume of the liquid phase, and the specific volume of the mixtures are available. A rough correlation of the formation volume as a function of pressure, temperature, and gas-condensate ratio has been presented. This correlation is considered applicable only to the range of conditions covered in this investigation for systems of similar nature and composition.

INTRODUCTION

Often a knowledge of the influence of temperature, pressure, and relative quantities of condensate and gas upon the volumetric behavior of fluids from a given field has been employed in estimating the conditions existing in the reservoir. The early work of Beecher and Parkhurst[1] and the more recent studies of the Dominguez[2] and San Joaquin Valley Fields[3] are examples of experimental studies of this character. Correlation of the volumetric behavior of naturally occurring hydrocarbon mixtures has proved to be feasible[4,5] at low gas-condensate ratios for fluids* from a single geographic area. Progress is being made in the prediction of the volumetric behavior of distillate systems at high gas-condensate ratios and pressures. However, the estimation of the retrograde[6,7] dew-point pressure still remains uncertain and probably can best be established by experiment. For this reason it appears of interest to make available experimental information about the volumetric behavior of mixtures of condensate and gas from five different parts of a single field. This material shows a rough similarity to data for mixtures of condensate and gas from San Joaquin Valley Fields.

In the present paper, no attempt has been made to coordinate the available information on the volumetric behavior of fluids from condensate fields. It appears hopeful that progress can be realized by the utilization of recently developed equations of state.[8] However, the primary problem in any such correlation is the proper identification of the components and constituents[9] of naturally occurring systems. Additional experimental information may be required to permit the determination of the values of the constants of the equation of state for each of the important components and constituents. The extension of experimental work in the region of retrograde phase behavior[7,10,11] for naturally occurring mixtures appears worth while since recent studies[12] indicate the existence of hetero-

Table 1 — Composition of Trap Samples

Component	Gas		Liquid	
	Mole Fraction	Weight Fraction	Mole Fraction	Weight Fraction
	System A			
Methane	0.9032	0.7792	0.0877	0.0136
Ethane	0.0467	0.0755	0.0573	0.0166
Propane	0.0247	0.0586	0.0605	0.0257
Isobutane	0.0094	0.0294	0.0526	0.0295
n-Butane	0.0069	0.0216	0.0500	0.0280
Isopentane	0.0029	0.0113	0.0455	0.0316
n-Pentane	0.0016	0.0062	0.0334	0.0232
Hexanes	0.0016	0.0074	0.0863	0.0717
Heptanes	0.0005	0.0027	0.1073	0.1036
Octanes and heavier	0.0005	0.0034	0.4194	0.6565
Carbon Dioxide	0.0020	0.0047	—	—
	System B			
Methane	0.8863	0.73894	0.12716	0.02159
Ethane	0.0457	0.07142	0.03658	0.01164
Propane	0.0344	0.07884	0.07678	0.03583
Isobutane	0.0144	0.04350	0.06663	0.04098
n-Butane	0.0085	0.02568	0.06418	0.03948
Isopentane	0.0040	0.01509	0.06235	0.04761
n-Pentane	0.0014	0.00525	0.03819	0.02916
Hexanes	0.0016	0.00717	0.07831	0.07142
Heptanes	0.0011	0.00573	0.10715	0.11364
Octanes and heavier	0.0006	0.00390	0.34269	0.58865
Carbon Dioxide	0.0020	0.00457	—	—
	System C			
Methane	0.8822	0.7283	0.1297	0.0213
Ethane	0.0487	0.0753	0.0368	0.0113
Propane	0.0298	0.0677	0.0619	0.0280
Isobutane	0.0130	0.0388	0.0562	0.0334
n-Butane	0.0094	0.0281	0.0505	0.0301
Isopentane	0.0045	0.0169	0.0552	0.0408
n-Pentane	0.0025	0.0094	0.0343	0.0254
Hexanes	0.0023	0.0103	0.1047	0.0924
Heptanes	0.0022	0.0112	0.1051	0.1079
Octanes and heavier	0.0004	0.0027	0.3656	0.6094
Carbon Dioxide	0.0050	0.0113	—	—
	System D			
Methane	0.9102	0.79095	0.13051	0.01969
Ethane	0.0443	0.07216	0 03727	0.01054
Propane	0.0212	0.05064	0.05324	0.02208
Isobutane	0.0087	0.02739	0.03630	0.01985
n-Butane	0.0049	0.01543	0.04666	0.02551
Isopentane	0.0027	0.01055	0.04651	0.03156
n-Pentane	0.0015	0.00586	0.03299	0.02239
Hexanes	0.0015	0.00709	0.08453	0.06852
Heptanes	0.0005	0.00271	0.11860	0.11178
Octanes and heavier	0.0015	0.01016	0.41339	0.66808
Carbon Dioxide	0.0030	0.00715	—	—
	System E			
Methane	0.9380	0.8568	0.0779	0.0109
Ethane	0.0322	0.0551	0.0291	0.0076
Propane	0.0139	0.0349	0.0348	0.0134
Isobutane	0.0038	0.0126	0.0262	0.0133
n-Butane	0.0034	0.0113	0.0767	0.0389
Isopentane	0.0019	0.0078	0.0363	0.0229
n-Pentane	0.0005	0.0021	0.0296	0.0186
Hexanes	0.0008	0.0039	0.0908	0.0683
Heptanes	0.0004	0.0023	0.1199	0.1049
Octanes and heavier	0.0001	0.0007	0.4787	0.7012
Carbon Dioxide	0.0050	0.0125	—	—
	System F			
Methane	0.9480	0.8929		
Ethane	0.0368	0.0650		
Propane	0.0120	0.0311		
Isobutane	0.0022	0.0075		
n-Butane	0.0009	0.0031		
Pentanes plus	0.0001	0.0004		
n-Pentane	0.0828	0.0543		
Hexanes	0.1804	0.1413		
Heptanes plus	0.7368	0.8044		

[1] References given at end of paper.

Manuscript received in the office of the Petroleum Branch June 11, 1951.

*For present purposes low gas-condensate ratios will be considered as those below 3,000 cu ft/bbl, and the region of high gas-condensate ratio will be limited to compositions containing more than 5,000 cu ft of gas per bbl of condensate. Mixtures containing between 3,000 and 5,000 cu ft of gas per bbl will be considered of intermediate gas-condensate ratio.

Table II — Properties of Less Volatile Portion of Trap Liquid Samples

	System A	B	C	D	E
Specific Gravity at 60°F. Atmospheric Pressure	0.7981	0.7881	0.7841	0.7903	0.7971
Average Molecular Weight	162.4	162.3	162.7	171.8	167.8

Cut No.	Specific Gravity 60°F/60°F	Kinematic Viscosity Centistokes 77°F	100°F	Viscosity Gravity Factor	Boiling Range °F	Weight Fraction
			System A			
10	0.7374	0.789	0.683	0.775	253-289	0.0608
10	0.7503	0.911	0.778	0.784	289-317	0.0619
10	0.7618	1.054	0.889	0.791	317-345	0.0629
10	0.7733	1.268	1.054	0.797	345-385	0.0638
10	0.7858	1.627	1.323	0.802	385-419	0.0648
10	0.7975	2.119	1.699	0.806	419-454	0.0658
10	0.8093	2.877	2.167	0.811	454-492	0.0668
30	0.8470	9.311	6.305	0.824	—	0.2097
			System B			
10	0.7342	0.7419	0.6579	0.7732	232-266	0.05503
10	0.7424	0.7975	0.7039	0.7795	266-288	0.05565
10	0.7549	0.9298	0.8069	0.7876	288-323	0.05660
10	0.7664	1.0906	0.9354	0.7940	323-349	0.05745
10	0.7776	1.3457	0.1301	0.7990	349-390	0.5830
10	0.7873	1.7786	1.4590	0.8002	390-432	0.05901
10	0.7978	2.3233	1.8568	0.8030	432-460	0.05980
10	0.8110	3.058	2.3781	0.8105	460-494	0.06080
20	0.8405	7.555	5.309	0.8210	494-	0.12601
			System C			
10	0.7384	0.758	0.661	0.7775	239-267	0.0572
10	0.7467	0.825	0.715	0.7838	267-292	0.0579
10	0.7571	0.939	0.807	0.7903	292-324	0.0587
10	0.7676	1.134	0.955	0.7942	324-365	0.0595
10	0.7780	1.409	1.182	0.7970	365-392	0.0603
10	0.7906	1.808	1.464	0.8042	392-430	0.0612
10	0.7996	2.367	1.866	0.8050	430-465	0.0620
10	0.8102	3.173	2.432	0.8084	465-500	0.0628
20	0.8379	8.151	5.422	0.8056	500-	0.1298
			System D			
10	0.7327	0.681	0.594	0.777	210-242	0.06269
10	0.7429	0.737	0.637	0.785	242-265	0.06356
10	0.7523	0.820	0.710	0.791	265-302	0.06436
10	0.7669	0.995	0.851	0.799	302-333	0.06561
10	0.7784	1.228	1.024	0.802	333-377	0.06643
10	0.7883	1.623	1.326	0.805	377-418	0.06744
10	0.7982	2.231	1.769	0.805	418-459	0.06829
10	0.8111	3.07	2.350	0.811	459-502	0.06949
20	0.8199	7.15	4.97	0.799	—	0.14030
			System E			
10	0.7515	0.772	0.668	0.7935	253-284	0.0662
10	0.7586	0.831	0.830	0.7905	284-307	0.0668
10	0.7721	1.000	0.884	0.8035	307-358	0.0680
10	0.7817	1.309	1.087	0.8065	358-395	0.0689
10	0.7916	1.765	1.440	0.8060	595-436	0.0697
10	0.8018	2.345	1.842	0.8080	436-470	0.0706
10	0.8109	3.045	2.333	0.8105	470-500	0.0714
10	0.8201	4.120	3.053	0.8125	500-540	0.0723
20	0.8362	8.456	5.797	0.8140	—	0.1473

geneous equilibria in hydrocarbon systems at pressures well in excess of 10,000 psi.

The terminology used in the discussion of the volumetric and phase behavior of naturally occurring mixtures has become somewhat standardized. In the present instance the terms will correspond to the glossary included in a recent publication[3] which closely follows earlier discussions. All volumetric quantities unless otherwise specified are considered as measured at 60°F and 14.73 psia. The term "liquid formation volume," which is analogous to "formation volume," refers to the ratio of the volume of the liquid phase of the mixture at the temperature and pressure in question to the volume of tank condensate associated with that mixture. At bubble point the formation volume and liquid formation volume are identical.

MATERIALS

Samples of condensate and gas were obtained from the surface separators of wells producing from separate parts of a field. They were collected in steel containers provided with valves at each end and originally were filled with natural gas at a pressure slightly above that of the atmosphere. Each sample container was thoroughly purged by flushing with a large excess of the fluid collected under conditions such that the pressure in the sample container was nearly equal to that in the surface separator.

At the laboratory, sub-samples were obtained by withdrawing the liquid or gaseous hydrocarbon through drying chambers packed with granular calcium chloride. The pressure within the original trap liquid sample containers was maintained during the withdrawal by the introduction of ethylene glycol. To avoid possible condensation of the trap gas sample, the containers were heated above 200°F before the withdrawal of the sub-samples. The same procedures were employed in the withdrawal of samples used in the determination of the volumetric and phase behavior of each of the several systems.

The samples were forwarded to an industrial laboratory where the composition of the trap liquid and the trap gas for each system was determined by fractional distillation. The mole and weight fractions of the components of the trap liquid and trap gas for each of the six restricted[6] multicomponent systems are presented in Table I. The average molecular weight of the heavier portion of the trap gas was estimated, and the average molecular weight of the octanes and heavier portion of the trap liquid was determined from the freezing point lowering of benzene. Table II presents some properties of the octanes and heavier portion of the trap liquid samples. They were separated into several parts by fractional distillation. The separation process was carried out at a reduced pressure to avoid thermal decomposition of the hydrocarbons involved. The weight fractions recorded in this table are based on a unit weight of trap liquid and their total equals only that fraction of the trap liquid represented by the octanes and heavier portion of the sample. Table III records the compositions of the tank condensate as determined from fractionation analyses of samples taken from the stock tanks of several wells.

LABORATORY METHODS

The procedures, equipment, and methods which have been employed in this investigation already have been described[9,12,14,15] and no significant modification from the original procedure was necessary in the present study. The composition of the experimentally studied mixtures is available,[16] and a

Table III — Composition of Tank Condensate

Component	System A[a] Mole Fraction	Weight Fraction	System B[b] Mole Fraction	Weight Fraction	System C[c] Mole Fraction	Weight Fraction	System D[d] Mole Fraction	Weight Fraction	System E[e] Mole Fraction	Weight Fraction
Methane	—	—	—	—	—	—	—	—	—	—
Ethane	—	—	—	—	—	—	—	—	—	—
Propane	0.0071	0.0024	0.02306	0.00831	0.0100	0.0035	0.01406	0.00459	0.0170	0.0056
Isobutane	0.0191	0.0085	0.03753	0.01781	0.0241	0.0111	0.01964	0.00845	0.0172	0.0074
n-Butane	0.0415	0.0185	0.05440	0.02582	0.0375	0.0172	0.03748	0.01612	0.0381	0.0164
Isopentane	0.0414	0.0229	0.05301	0.03123	0.0499	0.0285	0.04670	0.02494	0.0268	0.0153
n-Pentane	0.0445	0.0247	0.05046	0.02973	0.0544	0.0310	0.03443	0.01838	0.0358	0.0191
Hexanes	0.1079	0.0714	0.10600	0.07460	0.1152	0.0785	0.10458	0.06670	0.1078	0.0689
Heptanes	0.1449	0.1115	0.16343	0.13374	0.1658	0.1314	0.15859	0.11760	0.1443	0.1072
Octanes and heavier	0.5936	0.7401	0.51211	0.67876	0.5431	0.6988	0.58452	0.74322	0.6111	0.7601

Specific Volume and API Gravity at 60°F, 14.73 psi

[a] 0.02100 cu ft/lb 53.9° API
[b] 0.02150 cu ft/lb 58.2° API
[c] 0.02137 cu ft/lb 57.1° API
[d] 0.02113 cu ft/lb 54.9° API
[e] 0.022137 cu ft/lb 63.9° API

portion of these data constitutes Table IV.* The data have been presented upon a molal and weight basis and were established from a knowledge of the relative weights and the compositions of trap liquid and trap gas used in each of the mixtures.

EXPERIMENTAL RESULTS

The experimental measurements obtained for the several mixtures investigated are recorded[16] for systems A to F. In this tabulation the specific volume, the volume of the liquid phase per unit weight of mixture, formation volume, and the formation volume of the liquid phase[7] have been presented at a series of even-valued pressures and temperatures for each of the mixtures. Samples of these tabulations are shown in Tables IV and V.* A sufficient number of illustrative diagrams already is available[2,5] to make unnecessary the presentation of graphical representation of these data. From a qualitative standpoint, the behavior is similar to that of other naturally occurring condensate hydrocarbon systems.

At present, the prediction of retrograde dew point[6] is perhaps the most uncertain of the properties to be estimated by existing methods. The experimentally determined retrograde dew-point pressure is recorded in Table VI as a function of even values of the gas-condensate ratios for System F. The relation of the retrograde dew-point pressure and the gas-condensate ratio for this system is shown in Fig. 1. The dew-point pressure reaches a maximum at a gas-condensate ratio of approximately 8,000 cu ft/bbl and decreases rapidly at higher ratios. There was insufficient experimental background to establish with certainty the effect of gas-condensate ratio on the retrograde dew-point pressure for the other systems except within a limited range of conditions. The influence of temperature on the retrograde dew-point pressure for System F is presented in Fig. 2. A maximum in this pressure is encountered for the three gas condensate ratios involved at temperatures between 110° and 130°F. This type of behavior is similar to that occurring in other studies.[17]

*In order to conserve publication space only sample portions of Tables IV and V are presented here. For detailed paper order Document 3299 from American Documentation Institute, 1719 N Street, N.W., Washington 6, D. C., remitting $1.00 for microfilm (images 1 in. high on standard 35 mm. motion picture film) or $9.90 for photocopies (6 x 8 in.) readable without optical aid.

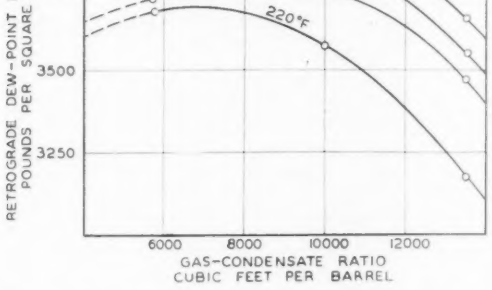

FIG. 1 — RELATION OF RETROGRADE DEW-POINT PRESSURE AND GAS-CONDENSATE RATIO FOR SYSTEM F.

Table IV — Sample of Composition of Experimentally Studied Mixtures

	System A			
	Weight Fraction Trap Gas 0.3220		Weight Fraction Trap Gas 0.4320	
Component	Mole Fraction	Weight Fraction	Mole Fraction	Weight Fraction
Methane	0.6798	0.2601	0.7478	0.3443
Ethane	0.0496	0.0356	0.0487	0.0421
Propane	0.0345	0.0363	0.0315	0.0399
Isobutane	0.0212	0.0294	0.0176	0.0294
n-Butane	0.0187	0.0259	0.0151	0.0252
Isopentane	0.0146	0.0251	0.0110	0.0228
n-Pentane	0.0103	0.0177	0.0077	0.0159
Hexanes	0.0248	0.0510	0.0177	0.0439
Heptanes	0.0297	0.0711	0.0209	0.0600
Carbon Dioxide	0.0015	0.0015	0.0016	0.0020
Octanes and heavier	0.1153	0.4463	0.0804	0.3745
Gas-Condensate Ratio — Cu Ft/Bbl		3216[a] 2665[b]		4960 4031

[a]Gas-condensate ratio expressed as cu ft/bbl of tank oil.
[b]Gas-condensate ratio expressed as cu ft/bbl of butanes and heavier hydrocarbons.

Table V — Sample of Volumetric Behavior of Experimentally Studied Mixtures

	System A			
Pressure, Psia	Specific Volume Cu Ft/Lb	Liquid Volume Cu Ft/Lb	Formation Volume	Liquid Formation Volume
	Weight Fraction Trap Gas = 0.3220 Gas-Condensate Ratio = 2,665 cu ft/bbl			
	40°F			
	(3,630)[a]			
B.P.	0.02987	0.02987	2.060	2.060
400	0.22036	0.01483	15.199	1.023
800	0.14125	0.01559	9.743	1.075
800	0.10269	0.01627	7.083	1.122
1,000	0.08015	0.01690	5.528	1.166
1,250	0.06272	0.01763	4.326	1.216
1,500	0.05180	0.01837	3.573	1.267
1,750	0.04463	0.01911	3.078	1.318
2,000	0.03980	0.01997	2.745	1.377
2,250	0.03651	0.02087	2.518	1.440
2,500	0.03426	0.02193	2.363	1.513
2,750	0.03274	0.02320	2.258	1.600
3,000	0.03168	0.02470	2.185	1.704
3,250	0.03086	0.02641	2.128	1.822
3,500	0.03020	0.02855	2.083	1.969

[a]Figure in parentheses represents bubble-point pressure expressed in pounds per square inch absolute.

Table VI — Retrograde Dew-Point Pressure

	System F Gas-Condensate Ratio cu ft/bbl				
Temperature °F	6,000	8,000	10,000	12,000	14,000
40	3,694[a]	3,758	3,740	3,628	3,408
70	3,850	3,890	3,863	3,754	3,549
100	3,928	3,956	3,920	3,808	3,599
130	3,943	3,960	3,911	3,790	3,581
160	3,904	3,904	3,845	3,712	3,487
190	3,825	3,804	3,731	3,576	3,329
220	3,714	3,676	3,576	3,388	3,100

[a]Retrograde dew-point pressure expressed in pounds per square inch absolute.

It has been found[2,5,8,9] that there exists a nearly linear variation in the formation volume with the gas-condensate ratio under isobaric-isothermal conditions. In the case of distillate fields the following expression[7] describes the volumetric behavior in the heterogeneous region with reasonable accuracy:

$$v = \frac{A r T}{P} \qquad (1)$$

The coefficient A of Equation (1) has been considered as a function only of pressure and temperature. The data recorded in Table VII represent average values of this coefficient for each of the mixtures investigated. There was an average deviation of 3.4 per cent of the individual values of this coefficient at a particular pressure and temperature from the quantities

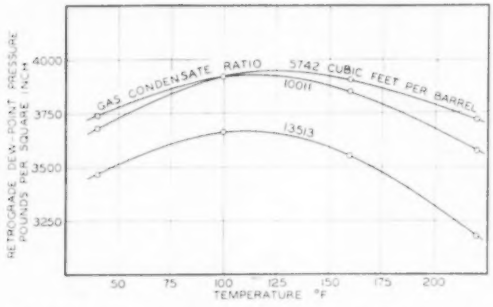

FIG. 2 — INFLUENCE OF TEMPERATURE UPON THE RETROGRADE DEW-POINT PRESSURE FOR SYSTEM F.

recorded in Table VII. This deviation was much larger than that encountered in two other investigations of gas-condensate fields.[5,17]* A comparison was made of the formation volumes computed from the coefficients in Table VII with experimentally determined values. The average deviation of the predicted and experimental formation volumes at 18 states chosen at random was 3.8 per cent. Table VIII presents a comparison of the coefficients which were obtained at several temperatures and pressures from the present studies and from measurements of the volumetric behavior of mixtures of condensate and gas from fields in the San Joaquin Valley[3] and Louisiana.[17] There appears to be a larger variation in this coefficient from one field to another than is experienced with the changes in gravity of the tank condensate from one zone to another in a particular field. It is expected that the coefficient of Equation (1) will be primarily a function of the relative quantity of the lighter hydrocarbons present rather than those of intermediate molecular weight. For this reason it is not surprising that minor changes in the gravity of the tank condensate did not influence the coefficients greatly.

*The legend of Fig. 1 of Reference 17 is in error and should read, "Pressure Specific Volume Product for System C Containing 0.8928 Weight Fraction Trap Gas." The discussion of Fig. 1 should be modified to " . . . . 0.8928 weight fraction trap gas."

Table VII — Values of Coefficient A
$A \times 10^4$

Pressure, Psia	40°F	100°F	160°F	220°F
600	4.39	4.65	4.85	5.01
800	4.22	4.54	4.77	4.95
1,000	4.07	4.44	4.70	4.90
1,250	3.91	4.35	4.63	4.84
1,500	3.79	4.27	4.58	4.81
1,750	3.72	4.22	4.55	4.79
2,000	3.70	4.19	4.54	4.78
2,250	3.70	4.20	4.54	4.78
2,500	3.73	4.23	4.57	4.80
2,750	3.83	4.29	4.61	4.83
3,000	3.98	4.38	4.67	4.87

Table VIII — Comparison of Volumetric Behavior of Fluids from Several Fields
Coefficient $A \times 10^4$

Pressure, Psia	100°F			160°F			220°F		
	San Joaquin	Louisiana 1	Louisiana 2	San Joaquin	Louisiana 1	Louisiana 2	San Joaquin	Louisiana 1	Louisiana 2
600	4.58	4.45	4.65	4.75	4.90	4.85	4.89	5.03	5.01
1,000	4.35	4.07	4.44	4.59	4.74	4.70	4.77	4.93	4.90
1,500	4.09	3.75	4.27	4.41	4.59	4.58	4.66	4.84	4.81
2,000	3.99	3.59	4.19	4.29	4.51	4.54	4.59	4.80	4.78
3,000	3.92	3.70	4.29	4.29	4.52	4.67	4.61	4.81	4.87

NOMENCLATURE

- A Dimensional coefficient
- P Pressure, psia
- r Gas-condensate ratio, cu ft/bbl
- T Absolute temperature, °R
- v Formation volume

ACKNOWLEDGMENT

This investigation was made possible by the financial support, cooperation and interest of the Texaco Development Corp. which also provided the samples for this experimental study. The Texas Co. carried out the analyses of the trap samples reported. R. H. Olds and Betty Kendall assisted with the preparation of experimental measurements in a form suitable for publication.

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MOBILITY RATIO—ITS INFLUENCE ON FLOOD PATTERNS DURING WATER ENCROACHMENT

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ABSTRACT

The results of potentiometric model studies and numerical computations are described. The purpose of these studies was to determine the influence of the mobility ratio on flooding efficiencies during water encroachment in petroleum reservoirs, in systems of regular well geometry.

The direct line drive well pattern having relative spacing distances of one and one-half to one was investigated for water to oil mobility ratios of 10, 1, and 0.1. The results of these studies indicate that the pattern sweep efficiency is very dependent upon the mobility ratio.

INTRODUCTION

The almost universal occurrence of water in the immediate neighborhood of oil-bearing sands lends considerable emphasis to the desirability of having a rational analysis of water encroachment into petroleum reservoirs. This problem has become increasingly important with the accelerated use of water injection for secondary recovery operations.

The water encroachment problem has been studied from both the theoretical and experimental viewpoints by Muskat.[1] He has formulated, in a precise manner, differential equations to express flow in a water encroachment system, and rigorous analytical solutions have been developed for the linear, radial, and spherical cases.[2] However, it becomes exceedingly difficult to solve the encroachment problem rigorously for any general two-dimensional system in which the shape of the two-fluid interface is not immediately evident from the geometry of the system. The difficulty lies in the fact that a rigorous analytical solution requires that the shape of the two-fluid interface be known simultaneously with its instantaneous position and with the pressure distribution on both sides of the interface.

Although this paper concerns the study of the two-fluid system of oil and water, the methods described in the paper are generally applicable to other systems of incompressible and immiscible fluids in which the displacing fluid sweeps the displaced fluid down to a residual value. In each region it is assumed there is only one mobile fluid and its mobility is constant throughout the region. The same procedure, with minor alterations, is applicable for gas injection systems provided the assumption can be made that both the displaced and displacing gases can be described by steady state formulas.

For the particular two-fluid problem considered in this paper, there is a relative permeability, K, and a viscosity, μ, associated with the water zone, and a different permeability and viscosity associated with the oil zone. The K/μ (mobility) value associated with a particular volume element of the porous medium, at any instant of time, will depend upon whether the element is ahead of, or behind the advancing interface. It is assumed that all volume elements ahead of the interface are characterized by the K/μ value for oil, while all the elements behind the interface are characterized by the K/μ value for water. That is, the K/μ value in the oil zone is constant throughout the oil zone, and the K/μ value in the water zone is also constant but different from the value in the oil zone. The symbols are defined at the end of the paper. The well pattern chosen for initial study is the direct line drive; the swept-out area at breakthrough was determined by two different methods which are described in the section on theory. These are:

1. Potentiometric analyzer
2. Numerical computation

The use of the potentiometric analyzer for studying water flooding problems is adequately described in the literature, particularly for cases where the mobility in the water zone is assumed equal to the mobility in the oil zone.[3,4,5]

[1]References given at end of paper.

Manuscript received in the Petroleum Branch, AIME, office, Aug. 7, 1951. Paper presented at the Fall Meeting of the Petroleum Branch in Oklahoma City, Okla., Oct. 3-5, 1951.

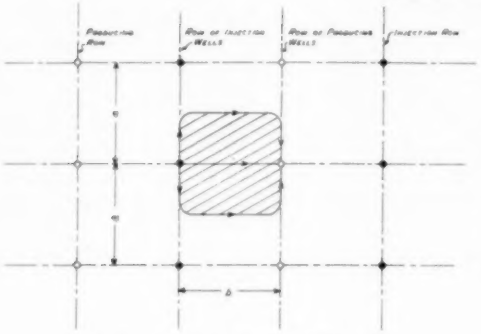

FIG. 1 — DIRECT LINE DRIVE WELL SPACING.

In the last 20 years, considerable interest has developed in the general use of numerical approximation methods for solving difficult mathematical problems when rigorous analytical methods proved impractical. To our knowledge, these numerical methods have not previously been applied to water encroachment problems,* although the numerical methods have been used by Southwell and co-workers in England to describe water flow under a coffer dam.[1]

Two specific examples are worked out in detail in this paper. The well pattern in both is the direct line drive consisting of alternate rows of injection and producing wells:

1. For the first example, the ratio of mobility values, water to oil $\frac{(K/\mu)_w}{(K/\mu)_o}$, is equal to 10. This problem was worked out by both methods described above.
2. The second example assumes a mobility ratio of 0.1; *i.e.*, the mobility for water is equal to 0.1 the mobility for oil. This second problem was examined only by the potentiometric analyzer method.

Results obtained using a mobility ratio of one to one were used as a reference in interpreting the effects of variations in mobility ratio on sweep efficiency.

DISCUSSION

Method

The geometry of the direct line drive well pattern used in this problem is illustrated in Fig. 1. This well geometry consists of alternate rows of injection and producing wells. The spacing of the direct line drive network may be altered by changing the b/a ratio of Fig. 1, where b represents the distance from a row of injection to a row of producing wells, and a is the distance between neighboring producing or injection wells. Since the sweep efficiency is dependent upon the b/a ratio, this ratio has been arbitrarily fixed at 1.5 for all investigations described in this paper. From the geometrical symmetry of the pattern, it is clear that the whole network may be represented by the rectangular section shown in Fig. 1 or 2. This rectangular section is used throughout this presentation to represent the line drive pattern.

A convenient yardstick for measuring the relative success of a flooding operation is the amount of oil displaced by the encroaching water. Though also dependent on a number of other considerations, the quantity of oil displaced is proportional to the area swept out by the water phase, since both the oil and water phases are assumed to be incompressible and immiscible. Techniques for determining the swept-out area or sweep efficiency for various well spacings are recorded in the literature. However, in all of these solutions the assumption is made that the K/μ (permeability to viscosity) ratio in the water zone is the same as the K/μ ratio in the oil zone. Based on laboratory information, is is believed that the mobility ratio $\frac{(K/\mu)_w}{(K/\mu)_o}$ may vary over a minimum range between 20 and 0.05, so it is desirable that this parameter be considered in determining sweep efficiencies.

This two-dimensional encroachment problem has not been solved rigorously for the case of mobility values differing on the two sides of a liquid-liquid boundary.[2] In this report an approximate solution to this problem is worked out by making use of the method of successive corrections.[3,4,5] This method is applied in the following manner:

1. Determine by numerical or analogue means the potential (pressure) distribution Φ_o in the oil zone and Φ_w in the water zone for an initial assumed position and shape of the interface.
2. Compute velocity vectors $\frac{(K \blacktriangle \Phi)}{\mu}$ at a selected number of well-distributed points on the interface.
3. Advance the selected points on the interface to a new position corresponding to some increment of time $\triangle t$.
4. Compute new values for the potential (pressure) distribution of the interface. The $(K/\mu)_w$ ratio is assumed to be constant in the new water zone. Similarly the $(K/\mu)_o$ ratio is constant throughout the new oil zone, but $(K/\mu)_w \neq (K/\mu)_o$.
5. Compute new velocity vectors; the whole step-wise process is then repeated until "breakthrough" occurs.

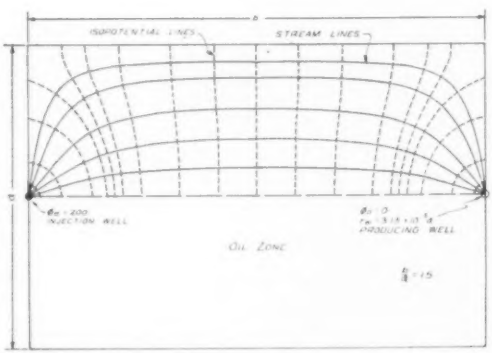

FIG. 2 — STREAMLINE AND POTENTIAL DISTRIBUTION FOR TYPICAL SECTION OF LINE DRIVE SPACING.

*It has been called to our attention that a paper entitled "Numerical Methods for Cycling and Flooding Problems," by C. H. Fay and M. Prats was presented at the World Petroleum Congress, June, 1951, at The Hague, Netherlands. They used a numerical method to study the flooding efficiency of a conventional five-spot well pattern for a mobility pattern of four to one.

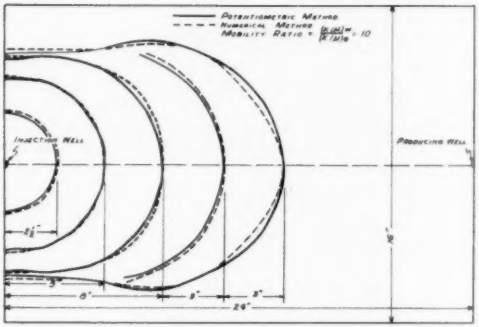

FIG. 3 — INSTANTANEOUS POSITIONS OF OIL-WATER INTERFACE FOR M = 10.

Mobility Ratio of 10

The above procedure can best be illustrated by examining the following problem:

Consider the two-well problem of the dimensions given in Fig. 2. This corresponds to a line drive "well spacing" of one and one-half to one as explained previously. Let $(K/\mu)_w = 10$ in the water zone and $(K/\mu)_o = 1$ in the oil zone. The permeability, K, may be measured in darcys and the viscosity, μ, in centipoises. We thus have a mobility ratio $M = \frac{(K/\mu)_w}{(K/\mu)_o} = 10$ for this problem.* Let us assume also that the injection well pressure is maintained at a constant value of $\Phi_i = 200$ atmospheres gauge throughout the investigation and similarly the producing well pressure is maintained at a constant value of $\Phi_p = 0$ atmospheres gauge.

Following Step 1 above, the pressure distribution and the streamline distribution are determined at that instant when injection commences (see Fig. 2). The exact manner in which the potential distribution may be calculated will be described in the section on Theory. The water-oil interface is now advanced to a new position as shown in Fig. 3 (drawn to represent the dimensions of an actual potentiometric model employed) which corresponds to some increment of time, Δt, that the water was injected. This interface position is designated 2½ in. since the nose of the interface was advanced arbitrarily 2½ in. out of 24 in. between wells of the model. Next, the pressure and streamline distributions on either side of the new interface position must be determined, based on the concept that the $(K/\mu)_w = 10$ throughout the now larger water-invaded zone and that $(K/\mu)_o = 1$, as before, in the remaining uninvaded region. Following this procedure the nose of the interface was advanced at specific increments of 2½ in., 5 in., 8 in., 11 in., 14 in., 17 in., 20 in., 22 in. out of a total distance of 24 in. between wells. Figs. 3 and 4 illustrate the positions of all the interfaces except that at 22 in. The increments of time, Δt, were allowed to change for each stage of advancement. The distance of nose advance was specified instead of the time increment in order to compare the swept areas for different mobility ratios.

The sweep efficiency then is determined from graphical integration of the flooded area at breakthrough as shown on Fig. 4. The percentile sweep efficiency is defined to be $\frac{\text{area of water zone at breakthrough}}{\text{total network area}} \times 100$. The sweep efficiency for the mobility ratio of 10 was 59.1 per cent as determined by the numerical method and 62.9 per cent as determined by the potentiometric method, or an average of 61.5 per cent.

Mobility Ratio of 1.0

It is of interest to compute the sweep efficiency by both the numeric and potentiometric techniques for the case of $M = 1$, particularly since such a solution has been described in the literature.[7] The flooded areas for $M = 1$ are shown in Fig. 5. The sweep efficiency determined by the numeric and potentiometric methods are 70.0 per cent and 71.6 per cent respectively. This is an average value of 70.8 per cent which is very close to the 70.74 per cent computed from Muskat's analytical solution. Such a close agreement with the theoretical solution is gratifying as a check on both the numeric and potentiometric methods.

Mobility Ratio of 0.1

Based on the analysis presented above, a comparison of 61.5 per cent sweep efficiency for $M = 10$ and 70.8 per cent efficiency for $M = 1$ indicates that approximately 10 per cent of the oil in place *could not* be swept out at breakthrough for $M = 10$ that was swept out for $M = 1$. This interesting result indicated that a flooding experiment should be run for the case where the mobility ratio $M = 0.1$. This problem was run off on the potentiometric analyzer following the steps described above. The details of operating the potentiometer analyzer will be discussed later. The successive advances of the interface are given in Fig. 6; the sweep efficiency is 86.6 per cent.

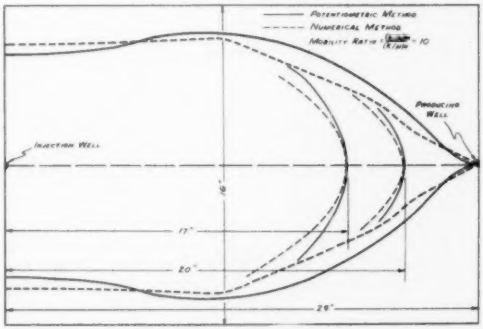

FIG. 4 — VARIOUS INTERFACE POSITIONS FOR M = 10.

*It should be understood that in a specific field problem the mobility ratio would have to be determined from auxiliary laboratory experiments and, of course, may have values different from 10.

COMPARISON OF FLOODED AREAS FOR THE VARIOUS MOBILITY RATIOS

A comparison is made between the flooded areas for the line drive pattern with mobility ratios $M = \frac{(K/\mu)_w}{(K/\mu)_o} = 10$, 1, and 0.1. The interfaces at breakthrough are shown in Fig. 7 where the curves are labeled "A," "B" and "C" for ratios of 10, 1, and 0.1 respectively. Curves "A" and "B" are average curves based on results of the two methods (potentiometric and numeric) of advancing the interface. Curve "C" was determined by the potentiometric method only.

The most significant fact is that the sweep efficiency is very much dependent upon the mobility ratio $M = \frac{(K/\mu)_w}{(K/\mu)_o}$, these efficiencies being 61.5 per cent, 70.8 per cent, and 86.6 per cent for ratios of 10, 1, and 0.1 as quoted previously. Such large changes in efficiency indicate that the effects of mobility ratio variations should be considered in practical field problems where careful economic studies must be made. The production rates also would be considerably different in the above three cases, although production rates have not been considered in this study.

A further interesting factor in this analysis is the shape of the interface itself at breakthrough for the three cases considered. All three curves of Fig. 7 have the typical "fingering" or "cusping" that must occur near the producing well. Because of the complexity of the problem, it would be impossible to predict a priori what the shape of the interface should look like for $M = 10$ based upon the shape of the interface curve for $M = 1$.

Muskat predicted the effect of the difference in viscosity between the fluids on the two sides of the interface (see page 478, *Flow of Homogeneous Fluids*:[5] "The effect on the encroachment of the water into the oil of higher viscosity will be an accentuation of the distortion and the sharpening of the 'fingering' or 'cusping' — for the single-fluid system. For the replacement of the higher viscosity oil by the encroaching water will evidently decrease the total resistance of the system and hence increase the average fluid velocities. The increase of the velocities, however, will be maximal along the main axis of the fingering where more of the oil has already been displaced by the water. This differential increase in the fluid velocities will, therefore, accentuate the distortion in such a way as to make the fingering more pronounced, although the effect will not become large until the interface approaches the vicinity of the output wells . . ."

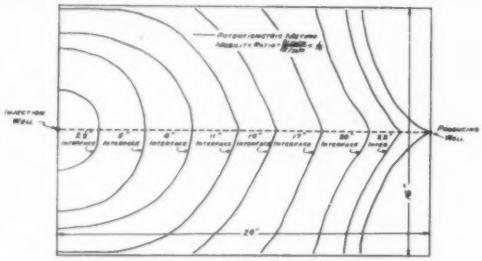

FIG. 6 — INTERFACE POSITIONS FOR $M = 0.1$.

In the above quotation, Muskat was interested in viscosity differences; the same argument applies to differences in K/μ ratios. Consider that the relative permeability in the water zone is the same as oil permeability. Then the mobility ratio $M = \frac{\mu_o}{\mu_w}$. Also let $\mu_o = 10\,\mu_w$ and assume that the oil is of higher viscosity than water as in the case that Muskat discussed. He predicted that the "fingering" would be more pronounced for this case ($M = 10$) than for the single-fluid system ($M = 1$). A comparison of these two cases is given in Fig. 7. Notice that the fingering for curve "A" ($M = 10$) is more pronounced than curve "B" ($M = 1$), and the flooded area is smaller for curve "A." The modification of curve "B" ($M = 1$) is just reversed when the mobility ratio $M = 0.1$. In the latter case, as indicated by curve "C," the flooded area is larger than for $M = 1$. No explanation is offered as to why curves "A" and "B" of Fig. 7 intersect near the producing well.

In a more recent article,[10] Muskat studied the effect of mobility ratios on water-drive systems producing from formations containing horizontal permeability stratifications and having zero vertical permeability. The general result is that when the mobility ratio of water to oil is larger than unity the channelling tendency, resulting from permeability stratification, becomes aggravated as the higher permeability zones become flooded out. Conversely, for mobility ratios less than unity, the flooding of the high-permeability zones will lead to a retarding and choking effect. It is interesting to note that the results described in the present paper confirm the concept that the "fingering" is aggravated for mobility ratios larger than unity and retarded for mobility ratios less than unity.

Still another instance may be cited where the "fingering" is aggravated for mobility ratios larger than unity and retarded for mobility ratios less than unity. Chatenever and Calhoun[11] have described the use of photomicrographic techniques for investigating water encroachment into a cell of spheres saturated with a high-viscosity oil. For this case where the so-called mobility ratio is less than unity, they observed that the flood front pattern had a stringy appearance as the water fingered through the flow bed. The condition of mobility ratio less than unity was represented by flooding the high-viscosity oil into a water-saturated cell. The flood front for this case appeared to advance with piston-like action, showing little tendency toward fingering and by-passing.

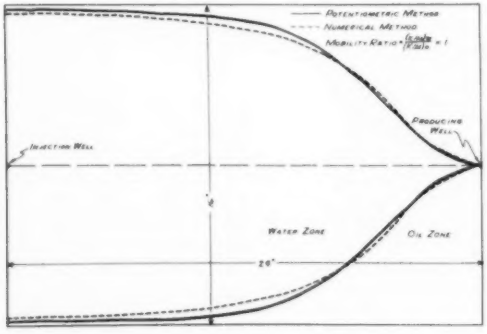

FIG. 5 — SWEEP PATTERN AT BREAKTHROUGH FOR $M = 1$.

EFFECT OF MAGNITUDE OF INCREMENTAL NOSE ADVANCE ON SWEEP EFFICIENCY DETERMINATION

In the actual case of water flooding, it is clear that the potential distributions in both the oil and water zones must vary continuously with time as the interface advances. The assumption is made that the history of these flow systems can be described in terms of a continuous succession of steady states, although the system is actually in an unsteady state of flow. In this investigation the nose of the interface was advanced in nine steps to the final (24 in.) position of breakthrough. At each successive advance of the interface, new streamline and/or potential fields were computed on a steady-state basis.

As shown in Fig. 3, the nose of the interface was advanced from 11 in. to 14 in., representing a three-in. increment. In order to compare the effect of increment size on the solution obtained it was thus desirable to advance the interface by smaller increments than three in. A comparison is made in Fig. 8 of interface advances from 11 in. to 14 in. by one-in. and three-in. increments. The comparison of Fig. 8, which is from potentiometric studies, shows that the area for the 14 in. interface by one-in. increments is about one per cent smaller than the swept area for three-in. increment advance of the nose. This indicates that the swept area at 14 in. nose position would be even smaller if smaller increments than one in. were taken; such effects are believed to be of secondary importance. This same procedure of advancing the interface nose from 11 in. to 14 in. by one-in. increments was computed numerically, and the results are similar to the potentiometric results given in Fig. 8.

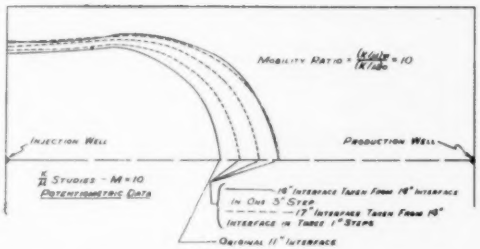

FIG. 8 — COMPARISON OF INTERFACE ADVANCES FROM 11 IN. TO 14 IN. BY ONE AND THREE-IN. INCREMENTS.

THEORY

Potentiometric Models

One of the methods of analysis discussed in a preceding paragraph is the use of potentiometric models to solve water encroachment problems. The basic theory of such models will be explained briefly here. There are excellent papers available on this subject by Muskat,[3] Lee,[4] and others.

These model studies are generally based on a two-dimensional idealization of the porous medium flow system by current flow in an electrolytic medium. The equation of continuity for the porous system is*

$$\blacktriangle \cdot v = 0 \quad \ldots \quad (1)$$

where v represents the macroscopic velocity vector.

The analogous continuity equation for the electrical system is

$$\blacktriangle \cdot i = 0 \quad \ldots \quad (2)$$

where i is the vector current density. The generalized Darcy's law may be written as

$$v = -\frac{K}{\mu} \blacktriangle P \quad \ldots \quad (3)$$

for two-dimensional flow where gravity forces are neglected.

Ohm's law becomes

$$i = \sigma \blacktriangle V \quad \ldots \quad (4)$$

where

σ = equivalent electrical conductivity
V = voltage
K = permeability
μ = viscosity
h = thickness of porous medium.

The continuity equation can now be rewritten by using Ohm's and Darcy's laws,

$$\blacktriangle \cdot \sigma \blacktriangle V = \blacktriangle \cdot \frac{Kh}{\mu} \blacktriangle P = 0 \quad \ldots \quad (5)$$

In order to build an electrolytic tank model to have geometric similarity with a fluid in a porous medium, Equation (3) must be equivalent to Equation (4). This indicates that the electrical conductivity, σ, must be proportional everywhere to $\frac{Kh}{\mu}$ even though K, μ, and h may vary from point to point in the x, y, plane. The effective electrical conductivity, σ, may be varied by changing the depth, h_e, of the electrolyte layer so that

$$\sigma = \sigma_e h_e \quad \ldots \quad (6)$$

where

σ_e = specific conductivity of the electrolyte
h_e = depth of electrolyte layer

we find then that

$$h_e = C \frac{Kh}{\mu} \quad \ldots \quad (7)$$

where C is a model scale factor.

Equation (7) can be simplified further for the water encroachment problem since it can be assumed that the sand thickness remains constant, or

$$h_e \propto \frac{K}{\mu} \quad \ldots \quad (8)$$

*List of Nomenclature given at end of paper. The symbol ▲ is used to represent the "del" operator because conventional symbol was not available.

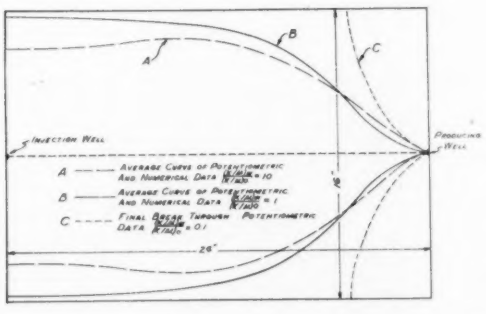
A
B
C
Injection Well
Producing Well
A —— Average Curve of Potentiometric and Numerical Data M = 10
B —— Average Curve of Potentiometric and Numerical Data M = 1
C ---- Final Break Through Potentiometric Data M = 0.1
24"

FIG. 7 — COMPARISON OF FLOODED AREAS FOR M = 10, 1 AND 0.1

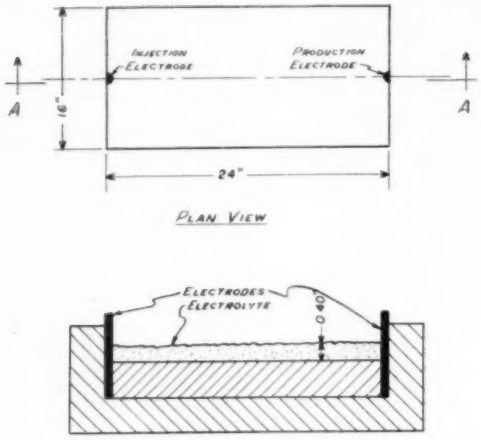

FIG. 9 — INITIAL POTENTIOMETRIC MODEL.

The requirement of geometrical similarity of voltage and pressure distribution will be insured if the electrolyte depth, h_e, is everywhere proportional to $\frac{K}{\mu}$. This concept can now be applied to the specific water drive problem where the mobility ratio $M = \frac{(K/\mu)_w}{(K/\mu)_o} = 10$. The electrolytic model initially has a uniform electrolyte depth of say 0.40 in. as shown in Fig. 9. The initial streamline and potential fields must be determined for this set-up and the interface advanced by standard procedures to the position illustrated in Fig. 10. The interface was advanced to this position by integrating time, t, along each streamline such that

$$\Delta t \cong \frac{(\Delta S)^2}{\Delta V} \quad \ldots \ldots \ldots \ldots \quad (9)$$

The incremental time, Δt, representing the time for a particle of fluid to travel a short distance ΔS. Each particle on the oil-water interface can then be advanced a short distance ΔS for some fixed time unit, Δt.

The interface for the first advance is shown in Fig. 10. Before advancing the interface again the condition $(K/\mu)_w = 10(K/\mu)_o$ must be approximated, which means $(h_e)_w = 10(h_e)_o$. This condition is shown in Fig. 10 where the electrolyte depth $(h_e)_o$ for the oil zone is 0.40 in. and the depth $(h_e)_w$ for the water zone is 4.0. This same process is repeated to get the successive advances of the interface that are illustrated in Figs. 3 and 4.

This technique of integrating time along a streamline for a short distance ahead of the interface is slightly different from the method involving successive corrections; however, the net result will be the same if the interface is advanced by very small increments.

Methods of Numerical Calculations

The most difficult step in calculating solutions of the type described earlier in this paper is to determine the potential or pressure distribution and/or streamline distribution for each successive advance of the interface. Some powerful numerical methods have been developed for finding solutions of La Place's equation, $\blacktriangle^2 P = 0$. The elegance of such numerical schemes is that the desired solutions are obtained in the form of numerical values of the function at a preassigned network of points covering the entire field where the differential equation is valid. Considerable progress has been made in recent years in applying numerical methods to practical problems. An extensive volume has been written by Southwell on this subject.[5] The specific method of interest involves replacement of the partial differential equation $\blacktriangle^2 P = 0$ by a corresponding difference equation, followed by numerical treatment of the difference equation.

Consider a potential field that is divided into a rectangular network, as in Fig. 11.

The La Placian equation $\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} = 0$ can be approximated by finite difference equations:

$$\left(\frac{\partial\Phi}{\partial x}\right)_m \cong \frac{\Phi_{m+1} - \Phi_{m-1}}{2(\Delta x)} \quad \ldots \ldots \quad (10)$$

$$\left(\frac{\partial^2\Phi}{\partial x^2}\right)_m \cong \frac{\Phi_{m+1} + \Phi_{m-1} - 2\Phi_{m,n}}{(\Delta x)^2} \quad \ldots \quad (11)$$

Similarly,

$$\left(\frac{\partial^2\Phi}{\partial y^2}\right)_n \cong \frac{\Phi_{n+1} + \Phi_{n-1} - 2\Phi_{m,n}}{(\Delta y)^2} \quad \ldots \quad (12)$$

Δx and Δy must be small for good approximation. For simplicity consider a square grid spacing where $\Delta x = \Delta y$.

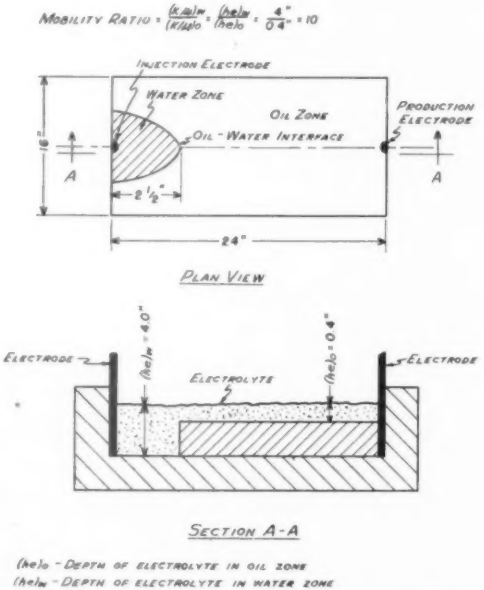

FIG. 10—POTENTIOMETRIC MODEL ALTERED FOR CHANGING OIL ZONE.

The finite difference approximation of $\blacktriangle^2\Phi = 0$ at the typical point, m,n in the x, y, plane will be

$$0 = (\blacktriangle^2\Phi)_{m,n} = \left(\frac{\partial^2\Phi}{\partial x^2}\right)_{m,n} + \left(\frac{\partial^2\Phi}{\partial y^2}\right)_{m,n}$$

$$= \frac{\Phi_{m+1} + \Phi_{m-1} + \Phi_{n+1} + \Phi_{n-1} - 4\Phi_{m,n}}{(\triangle x)^2} \quad . \quad . \quad . \quad . \quad (13)$$

The finite difference approximation of La Place's equation must be

$$\Phi_{m+1} + \Phi_{m-1} + \Phi_{n+1} + \Phi_{n-1} - 4\Phi_{m,n} = 0 \quad . \quad . \quad (14)$$

Or

$$\Phi_{m,n} = \frac{\Phi_1 + \Phi_2 + \Phi_3 + \Phi_4}{4} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

A simple physical interpretation would be that the value of $\Phi_{m,n}$ is approximated as being the arithmetic mean of its four nearest neighbors as shown in Fig. 11.

To solve for $\Phi_{m,n}$ one must write out Equation (15) for each mesh point in the x, y plane. There will be obtained a set of l linear algebraic equations for the l mesh points from which Φ is to be determined. This set of l equations may be evaluated by the usual rules of algebra. In a practical case where there necessarily must be a large number of mesh points, the direct solution of Equation (15) would be tedious and laborious for practical use, so approximation methods have been developed for obtaining the desired result without treating Equation (15) explicitly as a difference equation.

Perhaps the most convenient of these approximation techniques is the so-called "iteration method."[7,8] The advantage of this method for solutions of $\blacktriangle^2\Phi = 0$ is that it is simple to carry out regardless of the shape of the boundary. Also, it has been proved that the iteration process will always converge to the solution of the differential equation for very small increments.[12] This method will always work provided values of the function, Φ, or its normal gradient, $\frac{\partial\Phi}{\partial n}$, is specified at every point on the boundary.

The numerical results given in Figs. 4 through 9 were determined by this iterative process; however, the bulk of the computations were performed on IBM punch card machines. The chief advantages claimed for the punched card method are the speed with which the results can be obtained and the fully automatic procedure.

No rigorous attempt is made to justify the approximations introduced for both the potentiometric and numeric methods. First of all there are the approximations that are common to both methods or any other method that follows the basic procedure outlined above in this paper. Then, there are some approximations introduced that are associated only with the potentiometric method, and others that are associated only with the numeric method.

For instance, the potentiometric results are somewhat in error because of contact resistance, "three dimensional effect" at the abrupt change in electrolyte depth, and others. A different set of errors is introduced into the numerical calculations. The main difficulty in numerical work is the impracticability of greatly reducing the network spacing. Yet, small network spacing in the neighborhood of the interface is mandatory for accurate results.

It is pertinent to emphasize the manner in which the numerical and model solutions in this paper are tied to a known solution for the purpose of comparison. First, the numerical and model solutions were both checked against the analytical solution known for the mobility ratio of one to one. Then both numerical and model methods were used for the ratio 10

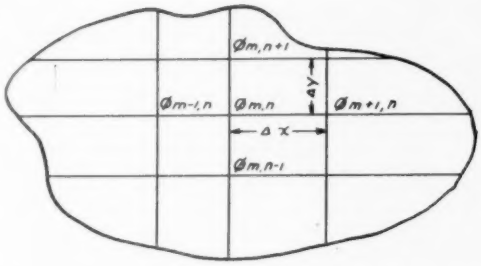

FIG. 11 — POTENTIAL FIELD DIVIDED INTO RECTANGULAR NETWORK.

with reasonably good comparison. It was then deemed safe to use the model alone for the ratio 0.1.

One source of error that is common to both potentiometric and numeric studies is that in all studies the interface was advanced to breakthrough in nine steps. It is possible that a considerably larger number of steps should be taken.

More model work of this nature is in progress and will be presented at some later date.

CONCLUSIONS

The results described in this paper clearly indicate that the sweep efficiency is very much dependent upon the mobility ratio $M = \frac{(K/\mu)_w}{(K/\mu)_o}$. These efficiencies are 61.0 per cent, 70.8 per cent, and 86.6 per cent for mobility ratios of 10, 1, and 0.1 respectively for the systems studied. This illustrates that the value of sweep efficiency can vary by 25 per cent for the change in mobility ratio from 10 to 0.1. Stated in other terms, the amount of oil recovered at breakthrough by water displacement is about 42 per cent greater where the mobility ratio is 0.1 as compared to the case where it is 10.

Such large changes in pattern sweep efficiencies indicate that the effects of mobility ratio variations should be considered in future reservoir analyses where careful economic studies are desired.

Emphasis is placed on the fact that the values of sweep efficiency reported here are not necessarily those to be obtained in practice, but are indicative only of the relative effects of the mobility ratio on an idealized system. In these studies no evaluation of the influence of variations of horizontal and vertical permeability upon sweep efficiencies was made, and only one well-spacing arrangement has been considered. When the effects of such variables as these are known and included in the determination of recovery efficiencies, substantially different values for over-all recovery efficiencies may result.

ACKNOWLEDGMENT

Acknowledgment is made to the management of the Field Research Laboratories, Magnolia Petroleum Co., for permission to publish this investigation. The writer is grateful to Paul Reichertz for suggesting the problem and for his active interest. H. W. Ballew and W. Wahl assisted in carying out the potentiometric and numeric studies. Acknowledgment is

also due A. C. Buchanan of the Magnolia Petroleum Co.'s Comptroller's Department for his effective help in the punch card operations.

NOMENCLATURE

K permeability in darcys
μ viscosity in centipoises
$\frac{(K/\mu)_w}{(K/\mu)_o}$ mobility ratio of water to oil
b distance from a row of injection to a row of producing wells (inches, in the potentiometric studies)
a distance between neighboring producing or injection wells (inches, in the potentiometric studies)
t time in seconds
S_e
S_b closed surfaces
v macroscopic velocity vector
Φ velocity potential
i vector current density
σ electrical conductivity
h sand thickness
C model scale factor
V electrical voltage
$\blacktriangle$ Nabla $\blacktriangle = \frac{i\partial}{\partial x} + \frac{i\partial}{\partial y}$

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DISCUSSION

By M. Prats, Shell Oil Co., Houston, Tex.

Aronofsky uses the close agreement between sweep efficiencies for the single fluid case obtained by numerical and potentiometric methods and the sweep efficiency obtained from Muskat's analytical solution "as a check on the numeric and potentiometric methods." This, in effect, is a check on one point of the production history, while the shape of the swept-out areas at water breakthrough do not indicate close agreement of production histories at later times, especially for the case where the mobility ratio is 10.

Although the following is (to some extent) a matter of opinion, I believe that, for a method of advancing fronts not involving successive corrections, the size of the steps taken is too large. The results of the study of the effect of the magnitude of size of steps on sweep efficiency determination may be highly misleading, since this study was carried out in the region where such effects would be small. If the study had been done in the neighborhood of the producing well, the results might have been startling.

The last remark arises from my experience doing similar work. Using a mobility ratio of 10 and a total electrolyte depth of one in., I found (from graphical measurements) that the refraction condition failed to be satisfied by ±20 per cent. I would expect that for a total electrolyte depth of four in. the effects of the third dimension would be even more pronounced. How well was the refraction condition met at the interfaces?

There is always room for improvements in any method based on approximations. Regardless of this, Aronofsky has well succeeded in simply and effectively showing the importance of the mobility ratio on flooding efficiencies.

DISCUSSION

By A. B. Dyes, The Atlantic Refining Co., Dallas, Tex., Member AIME

The importance of the effect of mobility of the phases on flood pattern efficiency and the consideration which must be given this factor in planning an injection operation cannot be overemphasized. We feel that the author has done a fine job, but should not do himself an injustice by limiting his subject to water encroachment. The analytical and experimental procedures which are used in studying the influence of the mobility of the phases on sweepout pattern efficiency apply equally well to gas injection operations. During the past year, some of us in The Atlantic Refining Co. have been involved in an investigation into the effect of this variable on the pattern efficiency of a five-spot flood. This study has not been completed and consequently the procedures employed and the final results will not be reported on until a later time. However, we would like to make a preliminary report of the results that have been obtained on a five-spot flood to supplement that reported by Aronofsky on the line drive.

In analyzing the results of this study, the mobility of the phases ahead of the displacing front to that behind the front has been called the mobility ratio. This is the definition used by Muskat in a previous publication. The selection of the mobility to be used as numerator and denominator in this ratio is arbitrary and this ratio could just as well be defined as the ratio of the mobility behind the displacing front to that ahead of the displacing front as used by the author of the preceding paper. We would like to urge the adoption of some

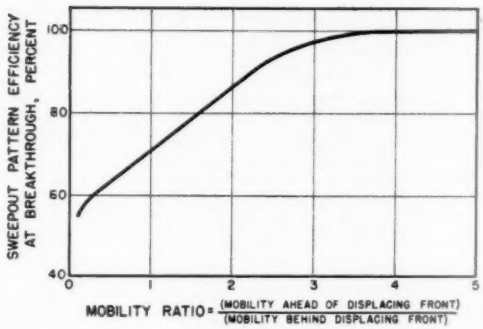

FIG. 1-A — EFFECT OF MOBILITY RATIO ON SWEEPOUT EFFICIENCY OF FIVE-SPOT FLOOD.

standard definition of this mobility ratio as related to flood pattern efficiency. Our preference is for the definition as used by Muskat and which has previously appeared in the literature.

In a given reservoir the mobility of the system must necessarily involve the mobility of each phase flowing. In a system of multiphase flow the mobility would be represented by the summation of the relative permeability-viscosity ratio of each phase. It is desirable to show the mobility ratio in a form applicable to multiphase flow problems. The reason for this is that the application of relative permeability data to the displacement of oil by water or gas indicates that in general two phases will be flowing in a portion of the reservoir behind the front, and in flooding operations of a reservoir depleted by solution gas drive two phases will be flowing in some portions ahead of the injected front.

The results which we have obtained showing the effect of the mobility ratio on flood pattern efficiency of a five-spot, considering that the specific permeability is constant throughout the system and that lengths on all sides of the five-spot are equal, are presented in Fig. 1-A. This figure shows that a mobility ratio equal to one yields a pattern efficiency of 71 per cent. This is in agreement with the values reported by Muskat. 71 per cent by calculation and about 73 per cent for potentiometric studies. As we increase the mobility ahead of the injected front with respect to that behind the front, we find that the flood pattern efficiency at breakthrough increases and approaches 100 per cent at a mobility ratio of four. For higher mobility ratios, the pattern efficiency is considered to be essentially 100 per cent. Conventional water flooding would generally fall in the region of 70 per cent to 100 per cent pattern efficiency at breakthrough for the system considered here. On the other hand, conventional gas injection would generally result in mobility ratios less than 1.0 and lower sweep-out efficiencies of only 55 to 70 per cent are indicated. At present the lower section of this curve below a mobility ratio of 1.0 has been defined by only one point. Consequently this section may be subject to some revision as this point is checked and other points obtained.

Comparison of the results obtained by Aronofsky for the line drive to these for a five-spot shows that changes in the mobility ratio result in a smaller change in the percentage sweepout efficiency at breakthrough for the line drive than for a five-spot. This might be expected from the difference in the geometry of the two systems. For the mobility ahead of the displacing front to that behind the front of 0.1, the line drive gives 61 per cent compared to 54 for the five-spot; each yields 71 per cent efficiency at a mobility ratio of one. At a ratio of 10 the line drive attains 87 per cent compared to 100 for the five-spot.

We must emphasize that the sweepout efficiencies reported are those at first breakthrough of the injected fluid. The possibility that we can exercise some control on the mobility ratio to change breakthrough recovery, points to a need for an accurate determination of the performance of a reservoir in the period after breakthrough whenever the sweep efficiency is less than 100 per cent. A thorough economic analysis of both phases of production will be required in justifying the additional expense that may be necessary to bring about changes in the mobility ratio.

AUTHOR'S REPLY TO MESSRS. PRATS AND DYES

Prats mentions that he did not have success in conducting a similar model experiment for mobility ratio of 10. He used a total electrolyte depth of one in. which means that the shallow depth was 0.1 in. Prats states that the refraction condition failed to be satisfied by ±20 per cent in his experiment. Our own experience with this problem is that the shallow depth of electrolyte should be larger than at least one quarter in. in order to get reliable results. The inaccuracies in constructing the model and non-uniformity of the electrolyte layer becomes critical for shallow depths in the range of 0.1 in. and this could account for a large portion of his ±20 per cent error. Certainly Prats is aware that the distortion of streamlines in the third dimension depends almost entirely on the *ratio* of depths of electrolyte and not on absolute magnitude, so there is some question as to the exact nature of the errors he is referring to.

Of course it is recognized that there must be some errors introduced by distortion of streamlines in the third dimension due to the abrupt change in electrolyte depth which represents the interface. Nevertheless these slightly distorted streamlines must still approximately obey the refraction condition, so it is possible to obtain useful information by making comparative studies of model experiments. There are several experimental techniques available that one could use to minimize the so-called "three dimensional effect" but such second order errors were neglected in this initial study.

Prats points out that it would be better if the interface was advanced by a larger number of steps in order to decrease the size of each step. The author would like to emphasize the importance of this observation. Perhaps, after more experience is gained, we will be able to correlate some relationship between errors in sweep efficiency and size of incremental advances of the interface.

Although Dyes is correct in pointing out that the procedures described in this paper for water-flooding are also valid for gas injection operations, the actual results presented in the text may or may not be applicable. There is some question whether Dyes is referring to displacement of liquid by gas or displacement of gas by gas. It should be remembered, however, that one of the fundamental assumptions involved in the calculations presented in the paper is that a discrete interface exists which is characterized by a discontinuity in the mobility ratio. If this assumption is valid for both of the above dis-

placement mechanisms (and we question the assumptions for at least the first mechanism) then the basic method described in this paper would be applicable with certain modifications. Such modifications are required by the fact that the voltage and current in the electrical system represent different properties in the gas injection case than in the water-flood case. Specifically, for example, in the case of gas cycling (isothermal flow) the voltage should represent mass gas flow (or volume gas flow under standard conditions). In the other case of liquid displacement by injected gas, still further complications arise which make it difficult to represent the system by a suitable model.

It does seem desirable that the term mobility ratio be standardized. Admittedly Muskat previously used the term mobility ratio to be the mobility of the fluid ahead of the displacing front to that behind the front; whereas in this paper the term mobility ratio is defined as the reciprocal to that defined by Muskat.

The author will not attempt to discuss the results of the five-spot tests presented by Dyes since it would be preferable to wait until the method is disclosed by which these results were obtained. The author has also studied the five-spot pattern by the potentiometric model method and these results will be presented at some later date.

The comments by Prats and Dyes are certainly appreciated. It is most gratifying to find out that other workers are concentrating on these problems. As more information becomes available perhaps the answers to the questions suggested by the discussers will be forthcoming. ★ ★ ★

The Drift of Things

. . . as followed by EDWARD H. ROBIE
Secretary AIME

A Business Manager

In late November and early December a considerable portion of our time was devoted to securing a business manager for Institute headquarters. The advisability of creating such a position was suggested in 1949 in the report of the Johnson committee. In that year, however, the Institute had a deficit of $72,000 so every effort was made to minimize expense. At that time, most of the duties that would normally be assumed by a business manager were given to Newell Appleton who became office manager, convention manager, purchasing agent, and assistant to the secretary. So many responsibilities were his that he could not devote the necessary time to all of the many things that needed attention. H. H. Vasoll, representing a firm that made a study of Institute head office procedures early last fall (JPT, Dec., 1951), therefore made a recommendation that "a business manager and controller from outside the present organization" be secured, who would supervise the work of the accounting, addressograph, purchasing, book and journal orders, filing, and mailing departments. He further recommended that Mr. Appleton be made administrative secretary, in which position he would act as head of an "Institute Activities Department." He would devote his time to convention planning, meeting arrangements, travel accommodations, membership control and promotion, and public relations, and would assist the secretary on special problems. Thus Mr. Appleton retains some of his former responsibilities and will take more of the load off our shoulders in the conduct of affairs at Institute headquarters. The rest of his former work will be in the province of the newly created "Business Office Department."

Peter J. Apol is the man finally selected for the post of business manager. He is a young man of 32, a native of Michigan and a graduate of the University of Michigan where he received a BS degree in business administration in 1940. He then spent three years in the Navy and has the rank of lieutenant in the U. S. Naval Reserve. Three more years were spent in the U. S. Maritime Service, as chief purser, and another year as chief paymaster for the Pope and Talbot Steamship Co. The last four years have been spent as head of the Greenland Construction Co., Greenland, N. H., chiefly engaged in building construction.

Apol will endeavor to increase the efficiency of Institute headquarters operations and remove all possible causes for complaints of individual members. He will co-ordinate as seems advisable the work of various departments and install such modern business office machinery as seems applicable to our needs.

Behind the Iron Curtain

Time was when the AIME was well represented in Russia, with both American and Russian engineers. Twenty years ago we had 57 members there. Now we have but one and he does not receive a journal.

In satellite countries the climate has been equally inclement. An application for membership from a man in Hungary was recently held up for some time because of lack of endorsers. Our only member in that country was a Mr. Simon Papp, and the applicant wrote that he was too ill even to be seen by members of his own family. This rather sounded like jail to us. Our suspicions were confirmed by an article in the Oct. 27 *Saturday Evening Post* reading in part as follows:

"The Hungarian American Oil Co., known as MAORT because of its initials in Hungarian, was a subsidiary of the Standard Oil Co. (N.J.). Paul Ruedemann (AIME member) and George Bannantine, its American supervisors, had been arrested and forced to confess to 'sabotage' that they had not committed. They had been deported without trial, after five days in prison, and MAORT had been expropriated without compensation on the basis of their 'confessions' . . . MAORT's general manager, the aged Simon Papp, had subsequently been sentenced to life imprisonment."

The Difference

Speaking of Russia, we like the story related by a recent applicant for AIME membership now doing a fine job in this country following some unpleasant years in eastern Europe. An international group was investigating industrial conditions in various countries. In the USSR they visited a factory which they were assured was entirely owned by the workers. Seeing a couple of automobiles out front, they asked who owned those. "Oh, those belong to the directors," they were told. Later, visiting a factory in this country, they inquired as to its ownership, and were informed it was owned by capitalists. "And what about those hundreds of cars parked outside?" "Those are all owned by the workers."

Irritating Our Best Friends

Though relations between the USA and Canada are entirely friendly, and armed conflict between the two countries is unthinkable, one of the editors of Canada's *Maclean's Magazine* recently told a New York Rotary Club audience that we do irritate each other. For instance, he said that many on this side feel that Canada isn't pulling its weight in the military effort generally and in the Korean war in particular. The real reason, he said, is that there is a limit to the force you can raise without conscription, and Canada does not have conscription. If Canada were in danger he indicated that conscription would probably be instituted. This strikes *us* as being a sane policy.

On the other hand, Canada is impatient with the mistrust that has developed in the United States over American foreign policy. They are afraid that we are going to drag them into a war. A second reason for Canadian anti-Americanism is that our differences at home undermine foreign confidence in American leadership. "In Canada we tend to get a picture of American policy as a catalog of calamity and ineptitude, conceived by men of no imagination and executed by men of no competence. We get the impression that that's what Americans think of their own government, and it is hardly surprising that some of us conclude that Americans ought to know."

Professionally, however, among mining men certainly, mutual respect and confidence are complete and the international boundary is unnoticed. Americans who go to the annual meeting of the Canadian Institute in Ottawa January 21-23 will be just as hospitably received as at their own meetings, and we hope to welcome equally as graciously the Canadian contingent who will be with us in New York February 18-21. ★ ★ ★

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 408 Trinity Universal Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded M-657, Y6427 and Y5945 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

PERSONNEL

♦ Geologist, MS, Eastern university. Experienced petrographer and seismic interpreter. Desires position as subsurface geologist with major company. M-657.

♦ Petroleum engineer with five and one-half years' experience in reservoir engineering, drilling, production, and workover operations desires employment with progressive independent as drilling and production engineer. Presently employed with major oil company in Gulf Coast, thirty years of age, and non-reservist. Prefer employment in Louisiana-Texas Gulf Coast or East Texas. Code 159.

POSITIONS

♦ Combustion engineer with BS in mechanical, chemical, petroleum or combustion engineering. Preferably MS in combustion engineering, and not less than eight and preferably ten years in combustion engineering field. Experience should cover theory of combustion, liquid fuels and design and maintenance of domestic and industrial burners. Must be able to supervise and direct the activities of a group along a given line in his field, and should be able to train personnel in matters concerning his field. Salary open. Location, Brooklyn, N. Y. Y6427.

♦ Sales engineer, young, mechanical or chemical graduate, with industrial experience, to sell petroleum and chemical process equipment, valves, gauges, etc. Salary, $5,000-$6,000 a year to start, eventually higher on commission basis. Location, New York, N. Y. Y5945.

♦ A principal New York City banking establishment is seeking a graduate in petroleum geology, preferably one with several years' experience in the field and with some practice in estimation and valuation of oil and gas reserves. This position offers experience in oil and gas research studies and property appraisals as well as the correlative advantage of experience in the field of financing and the financial aspects of the petroleum industry. Financial stability and probability of advancement are excellent. Code 537.

Gas Lift

Continued from Page 20, Section 1

Where:

D — maximum operating depth in feet from surface
P — surface operating pressure of valve — psi
P_t — flowing tubing pressure — psi
G — average flowing fluid gradient — psi/ft

This formula is an approximation; as the gradient changes with distance from the surface and the weight of the casing gas column is not considered.

A factor to consider in an aeration type of flow is the result of excessive operating pressure. When higher pressures are used in an attempt to work lower in the hole, admission of additional gas lowers the flowing gradient of the tubing fluid column beyond a point of efficiency.

When this exists, a reduction in quantity of fluid lifted occurs because friction loss in the tubing creates back pressure to the extent that the flowing bottom hole pressure is raised instead of lowered. This tends to reduce the differential between reservoir pressure and flowing bottom hole pressure, thereby reducing the quantity of fluid flowing into the well bore. ★ ★ ★

— It's a Fact —

Total income of all Americans earning more than $6,000, after payment of federal income taxes, amounts to $6.5 billion. That is less than the amount authorized for foreign aid last year.

Proposed for Membership, Petroleum Branch

Total AIME membership on Nov. 30, 1951, was 17,405; in addition, 2,079 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Carless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mollison, John T. Sherman, Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. A. Clark, Jr.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of [illegible] ar-lic nt. Details of the objection should follow by air mail. The Institute desires to extend privileges, but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; A, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

ARKANSAS

El Dorado — Gorishek, Rudolph (J) (C/S-S-J).

CALIFORNIA

Brea — Krueger, Roland F. (M).
Huntington Park — Solum, James R. (J).
La Jolla — Barbarick, Harding (J) (C/S-S-J).
Los Angeles — Downey, Charles E., Jr. (J) (C/S-S-J); Johnston, Elizabeth J. (M).
San Gabriel — Drake, Lee A. (J).
San Francisco — Weber, John G. (J) (R,C/S-S-J).
Taft — Aseltine, Richard J. (J) (C/S-S-J).
Whittier — Hart, Francis D. (C/S-S-J).

KANSAS

Great Bend — Collins, Ora C., Jr. (C/S-S-J).
Liberal — Godfrey, George W. (A).

LOUISIANA

Pt. Sulphur — Kosarek, Charlie J., Jr. (C/S-S-J).
Lafayette — Jones, Frank E. (C/S-J-M); Yount, Byrd T., Jr. (J).
New Orleans — Terrell, Timothy H. (M) (R, C/S-J-M); Prior, Frank O., Jr. (J); Zimmerman, Robert M. (J).
Metairie — Vice, William B., Jr. (J).
Pointe Ala Hache — Snoddy, William G. (A).

MISSISSIPPI

Washington — Moses, William S. (J).

OKLAHOMA

Shiatook — Knapp, Harold H. (R,C/S-S-A).
Tulsa — McCormick, Joseph C. (M) (R).

TEXAS

Alice — Bozeman, John F., Jr. (J).
Alvin — Clark, James D. (M) (C/S-J-M).
Austin — Alani, Ghalib H. (J) (C/S-S-J).
Bellaire — Melsheimer, Albert H. (M).
Clarkwood — Adams, Fred B. (J).
Corpus Christi — McCauley, Charles F. (M); Wilson, Harold B. (M).
Dallas — Hawkins, Murphy E. (C/S-S-J); Meyer, L. J. (M) (R,C/S-J-M).
Fort Worth — Moreland, Leonard G., Jr. (C/S-S-J).
Houston — Buell, Vincent F. (M); Gollnick, Robert L. (M); Hiam, Edwin W. (J); Hopkins, Wilbur B. (C/S-J-M).
Kilgore — Sole, William G., Jr. (J) (R,C/S-S-J).
McAllen — Gracey, Joe P. (J).
Midland — Johnston, David (M) (C/S-J-M).
Odessa — Kirkpatrick, Richard P. (R,C/S-S-J); Rodman, Earl G. (J) (C/S-S-J).
Olney — Jordan, James E. (J) (C/S-S-J).
Wichita Falls — Moffatt, Lowell G. (J).

WYOMING

Calpet — Arnold, Donald Ray (C/S-S-J).
Casper — Bischoff, Robert M. (M) (C/S-J-M); Yaquinclch, John G. (M).
Newcastle — Coxon, Donald A. (J) (C/S-S-J).
Rock Springs — Kratka, Frank H. (C/S-J-M).

ALASKA

Jackson — Winter, Claude V. (J) (C/S-S-J).

SAUDI ARABIA

Dhahran — Hiestand, Frank I. (J) (C/S-S-J).

TURKEY

Ankara — Cayci, Ahmet C. (C/S-J-M).

VENEZUELA

Barcelona — Holmes, Joseph A. (J).
Caracas — Davenport, Gene S. (J). ★ ★ ★

Technical Publications Committee Installed

Personnel of the AIME Technical Publications Committee, which took office for the ensuing year on Oct. 15, follows:

J. I. Laudermilk, chairman; Charles H. Lambur and Vinton H. Clarke, vice-chairmen; E. J. Kennedy, Jr., secretary; Robert H. Aborn, J. R. Atkinson, W. H. Callahan, Charles W. Eichrodt, Francis B. Foley, E. V. Gent, M. B. Gentry, M. D. Hassialis, W. H. Loerpabel, Robert D. Nininger, Earl W. Palmer, J. S. Smart, Jr., with Joe B. Alford, John Beall, E. O. Kirkendall, R. E. O'Brien and E. H. Robie members ex officio.

This committee relies to a large extent on Divisional Auxiliary Publications Committees for its action on the acceptance or rejection of papers, but considers matters of policy, and budgetary limitations. ★ ★ ★

Nominating Committee Additions Named

Certain additions to the personnel of the Nominating Committee for AIME Officers in 1953 were approved at the Dec. 5 meeting of the Executive and Finance Committees. Proposed by the executive committee of the Council of Section Delegates: M. Gensamer, School of Mines, Columbia University, New York 27, N. Y. (with Max Ball, 1025 Vermont Ave., Washington 5, D. C., as alternate.) Alternate from the Southern California Section: Basil Kantzer, Union Oil Co. of California, 617 W. 7th St., Los Angeles 14. These names should be added to the list published in the December issue. ★ ★ ★

AIME to Welcome 32 To Its Legion of Honor

Thirty-two members of the Institute who have been on the rolls for 50 years will be honored next month when they are added to the Institute's Legion of Honor, and receive a gold pin emblematic of the distinction. Each is invited to sit at the head table at the Annual Banquet of the AIME Annual Meeting Feb. 18-21 to receive the honor, but where this is impossible it will be individually bestowed. The list of those believed still living who joined the AIME in 1902 follows: Lawrence Addicks, H. A. Barker, W. S. Boyd, Seymour K. Bradford, Davenport Brown, Russell T. Cornell, H. E. Crawford, Augustus B. Emery, Augustus H. Eustis, Fredric A. Eustis, Edward P. Fleming, Fernando C. Fuchs, A. H. Jameson, J. B. Landfield, Alexander Leggat, John H. Lidgerwood.

Also, Lesley McCreath, D. I. Miller, Henry C. Morris, Edwin L. Oliver, Robert W. Pringle, A. L. J. Queneau, Milnor Roberts, William Russell, Reno H. Sales, Hoval Arnold Smith, Howard D. Smith, A. D. Sproat, H. H. Utley, Ethceredge Walker, W. R. Whitney and L. Webster Wickes. ★ ★ ★

Texas A&I College Chapter Authorized

A new Student Chapter of the AIME was authorized by the Board at its Dec. 5 meeting — at the Texas College of Arts and Industries, Kingsville, Texas. The group is interested in petroleum and natural gas engineering, and the curriculum has been accredited by Engineers Council for Professional Development. ★ ★ ★

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Personals

LESLIE G. CARRUTH is now in charge of the recently opened Corpus Christi, Tex., office of L. R. Carter and Co., ad valorem tax consultants for independent oil producers and refiners. A petroleum engineer, Carruth has been associated with the firm for the past two years, located in the central office in Dallas. His new address is in the Wilson Tower in Corpus Christi.

+

NORMAN A. OLANSEN is now with The Texas Co., West Columbia, Tex.

+

S. ANTHONY STANIN, Phillips Petroleum Co., has been transferred from Ardmore, Okla., to Bismarck, N. D.

+

BENJAMIN R. PEARMAN has joined the Stanolind Oil and Gas Co. at Levelland, Tex.

+

JOHN A. MCCUTCHIN has accepted a position with Whitehall Canadian Oils, Ltd., Calgary, Alberta.

+

ROY H. SMITH has become chief production engineer of Stanolind Oil and Gas Co., replacing LEWIS FINCH, JR., now chief engineer, producing department. Smith joined Stanolind in June, 1934, immediately after receiving his BS degree in petroleum engineering from the University of Tulsa. He served as field engineer in various areas in Texas. In 1943, he became division engineer of the Central Division. Since June, 1949, Smith has been assistant to the manager of the producing department. He is a past chairman of the Mid-Continent Section of AIME.

EUGENE LIPSTATE is now a geologist with the Ryan Consolidated Petroleum Corp., Dallas.

+

JACK D. SCHAFER has joined DeGolyer and MacNaughton, Dallas. He had been with The Atlantic Refining Co., Midland, Tex.

+

GLEN R. HORTON, geologist, is now with the Sinclair Oil and Gas Co., Casper, Wyo.

+

EDGAR L. ELY has accepted a position as junior petroleum engineer with the Chicago Corp., Bishop, Tex.

+

ROBERT F. BRONTE is a well tester for the Gulf Oil Corp., Baytown, Tex.

+

MICHAEL J. POPOVICH has become associated with the Texas Eastern Transmission Corp. in Shreveport, La. Formerly an engineer with Sohio Petroleum Co. in Oklahoma City, Okla., Popovich served as secretary-treasurer of the Oklahoma City Section of AIME for the past year.

+

ROBERT SIEGEL, Socony-Vacuum Oil Co., Inc., New York, is now with the Socony-Vacuum Overseas Supply Co., Fort Lee, N. J.

+

WALTER GRANLUND has become associated with the U. S. Geological Survey, Topographic Div., Denver, Colo.

+

HENRY J. SHERMAN is now employed as a geologist for the Schermerhorn Oil Corp., Tulsa.

+

FREDERICK LARSEN has joined the California Co., Rangely, Colo.

THOMAS C. FRICK has been transferred to Corpus Christi, Tex., as coordinating manager of the Atlantic Refining Co.'s new regional office there. A graduate and former staff member of the University of Tulsa, Frick has been with Atlantic since 1941. Entering the company as job analyst, he became district superintendent in East Texas in 1944. In 1947 he went to Odessa, Tex., as district superintendent. Since 1949 he has been located in Midland as division operations supervisor in charge of drilling, producing, engineering and material activities for the company in West Texas and New Mexico.

+

ANDREW H. CARPENTER, formerly engineer with the production dept., Cities Service Oil Co., Oil Hill, Kansas, is now with the Phillips Petroleum Co., Big Spring, Tex.

+

L. COURTNEY DECIUS is vice-president, Cyprus Oil Co., Los Angeles.

+

HENRY G. ABADIE has been appointed chief petroleum engineer for the Long Beach Oil Development Co. He had been senior production engineer.

+

GORDON R. STINE, formerly with Cable and Stine, has opened his office in Wichita Falls, Tex., for the general practice of petroleum engineering.

+

CHARLES H. BLANKENHORN, JR., is now with the Sunray Oil Corp., Snyder, Tex.

+

JAMES W. BOWLER has joined the Socony-Vacuum Oil Co., Inc., New York.

+

JOHN A. JONES is now employed by the Slim Rea Drilling Co., Mt. Vernon, Ill.

Committees Named For Annual Meeting

The 1952 Annual Meeting of the AIME will be held in New York City Feb. 18-21. The Petroleum Branch program and abstracts of papers to be given may be found on Page 22. Section 1. Members of the various committees now functioning in the setting up of the four-day Institute-wide meeting are listed below.

ARRANGEMENTS
Francis Cameron, *Chairman**

RECEPTION
Philip D. Wilson, *Chairman*
Howland Bancroft
John G. Baragwanath
Lester E. Grant

BANQUET
M. B. Gentry, *Chairman*
Louis C. Raymond, *Vice-Chairman*
Mrs. Domingo Moreno
Mrs. Thorne E. Lloyd
Parke A. Hodges
Ernest V. Gent
Frank G. Breyer
Fred W. Hanson
J. R. Atkinson
W. A. Clark, Jr.

DINNER-SMOKER
Louis C. Raymond, *Chairman*
Maxwell L. McCormack, *Vice-Chairman*
R. L. McCann
Frank R. Milliken
David Swan

WELCOMING LUNCHEON
W. J. Turner, *Chairman*
Mrs. John P. Dyer
H. W. Hitzrot
R. D. Mollison
H. G. Moulton

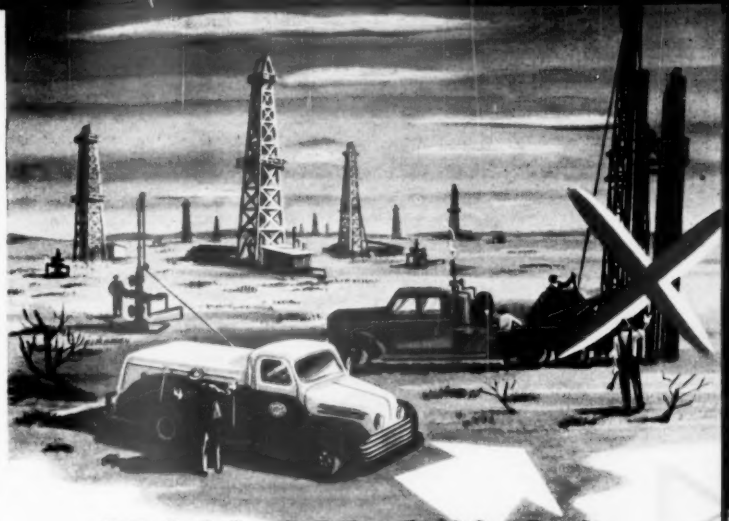
INFORMAL DANCE
Ira K. Hearn, *Chairman*
David T. Steele
George P. Lutjen

HOTEL
Robert H. Ramsey, *Chairman*
John H. Ffolliott
Howard L. Waldron
Robert B. Fulton

INFORMATION
Alvin Knoerr, *Chairman*
George P. Lutjen
Theodore Marvin

COCKTAIL PARTY
Russell H. W. Chadwick, *Chairman*
C. Phillip Jenney
Joseph A. Wiendl

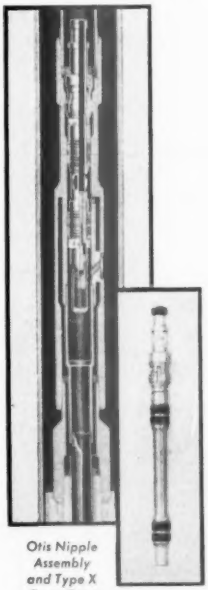
*Arrangements Committee: Chairmen of the above committees plus Executive Committee of New York Section.



CROSS OFF THIS OLD WAY TO CROSS OVER

flow courses in two-zone wells

Otis "Selective" Cross-Over Nipple Assembly and Wire Line Chokes



Otis Nipple Assembly and Type X Cross-Over Flow Choke

Otis Type R Choke for Parallel Flow

The Otis service truck and the contractor's workover unit shown above are performing the same operation — crossing over the flow courses in a two-zone well. The Otis truck is on a well in which an Otis "Selective" Cross-Over Nipple Assembly is installed, and the Otis wire line crew has pulled an Otis parallel flow choke from the nipple and is going back in the hole with an Otis cross-over flow choke that will produce the upper zone through the tubing and the lower zone through the tubing-casing annulus. This is a simple and economical method of crossing over flow courses by means of wire line operations at the surface, at a minimum of downtime — making it unnecessary to kill a well and pull and re-run tubing to cross over. The Otis cross-over assembly consists of a landing nipple, a tail pipe, and a special sub to connect the Otis cross-over head to the packer (an Otis Type C, Baker Model D, or similar packers). The assembly is permanent sub-surface equipment run with the packer. After the packer is set and surface connections are made up, either the parallel flow or cross-over choke is run in and locked in the nipple, using a regular Otis high-pressure lubricator and wire line tools.

Before you complete — or recomplete — another well in these days of high production costs, ask your nearest Otis office for full particulars on this equipment. There's no obligation, of course.

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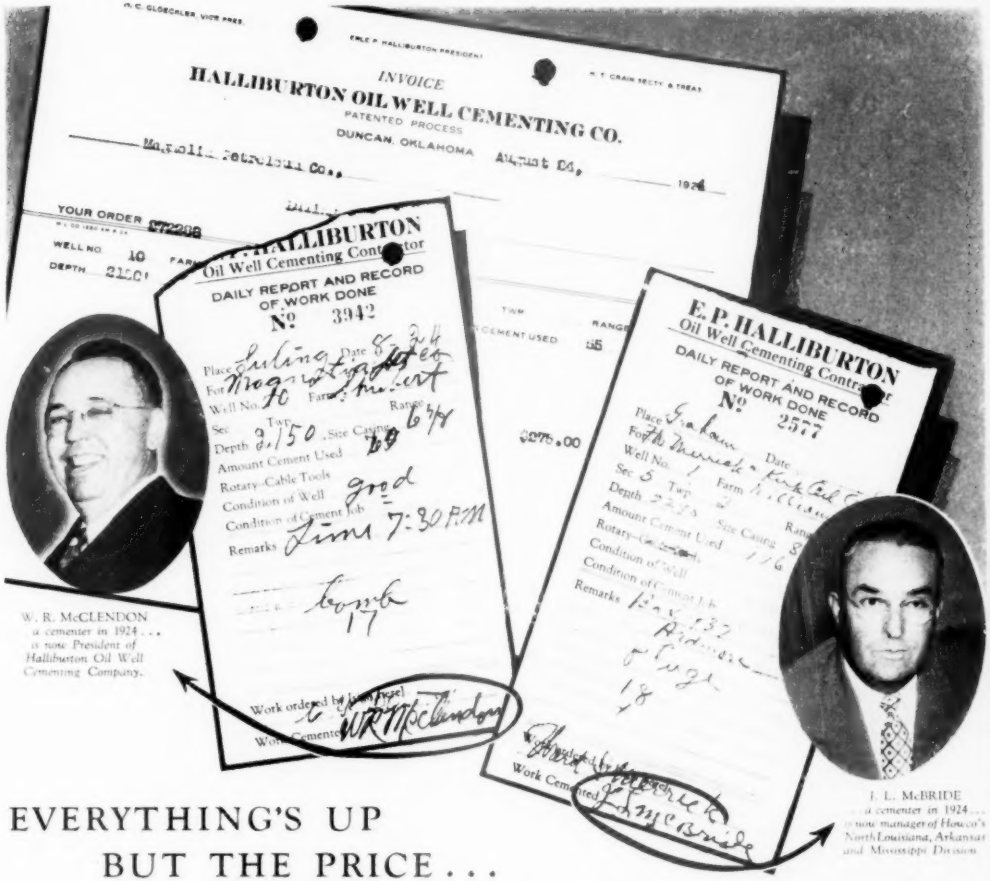

EVERYTHING'S UP BUT THE PRICE . . .

The men have gone up. W. R. McClendon, a cementer in 1924, is now President of the Halliburton Company. J. L. McBride, also a cementer in 1924, is now manager of Howco's North Louisiana, Arkansas, and Mississippi Division.

The cost of cementing trucks has gone up—from $6,000 in 1924 to more than $50,000 today.

Cementers' wages have gone up by more than 70%.

Only one element of a cementing job has gone down. The price of the average job today is less than it was in 1924!

Earle P. Halliburton

Chairman of the Company

HALLIBURTON OIL WELL CEMENTING CO.
Duncan, Oklahoma

Rock Bit Performance

Continued from Page 13, Section 1

case, of less than approximately 12,000 lb is carried, an increase of the nozzle velocity from 182 ft/sec to 286 ft/sec offers no advantage. This additional nozzle velocity is effective only when additional weight is applied to the bit or if the bit was in a balled up condition prior to the application of this additional velocity.

We believe that this also indicates the reason why no general figure for minimum effective jet velocity can be given unless weight, bit type, formation, and all of the other factors affecting bit penetration are also specified. In any event, exception must be taken to the statement that " . . . this velocity (175 ft/sec) is inadequate under all conditions." Based on results obtained on a light contract rig in North Texas, a well drilling with conventional bits required 36½ per cent more rotating hours and 42 per cent more bits when compared with a jet drilled offset well. The maximum velocity obtained with the jet bits in this case was approximately 175 ft/sec. While this velocity may not have been adequate, in this case it was certainly not inadequate. As a result of this comparison, it is our belief that jet bits may be economically utilized on much smaller rigs than is generally believed possible. ★ ★ ★

California Gas Supply

Continued from Page 17, Section 1

cation of current rules and practices to facilitate the supplying of gas service."

Among the objectives of the proceeding, as expressed in the order, was that of assembling and consolidating information regarding the ability of the gas utilities to meet the increasing demands occasioned by the national defense and war needs. To attain this objective, the commission requested preparation of estimates of gas supply and availability to meet annual and peak day requirements.

Because the investigation was to be state-wide in scope, and because the Commission, in its order, expressed the hope that " — the state-wide cooperative effort to insure maximum availability of gas throughout the state can be continued and made fully effective —," a committee composed of representatives of the state's major gas utility companies was formed to prepare and consolidate the requested information.

This committee developed forecasts which indicate the need for additional gas supply to meet the state's estimated peak day firm demand by the winter of 1952-53, should extreme peaking conditions occur coincidentally throughout the state, as happened in the winter of 1948-49. It is expected that these added requirements can be met by increasing deliverability from present seasonal storage, by development of additional storage projects, by augmenting present primary supplies, or by a combination of these steps. The latter course is being pursued as the means best suited to the assurance of a long range supply to firm customers.

As was mentioned at the beginning, Californians are traditional gas customers. The state and the gas industry have grown up together. Since the gas utility companies are primarily obligated to supply the demands of their firm users, upward trends in population and gas usage are being watched closely, and every effort is being made to keep well ahead of the increasing demands for gas. ★ ★ ★

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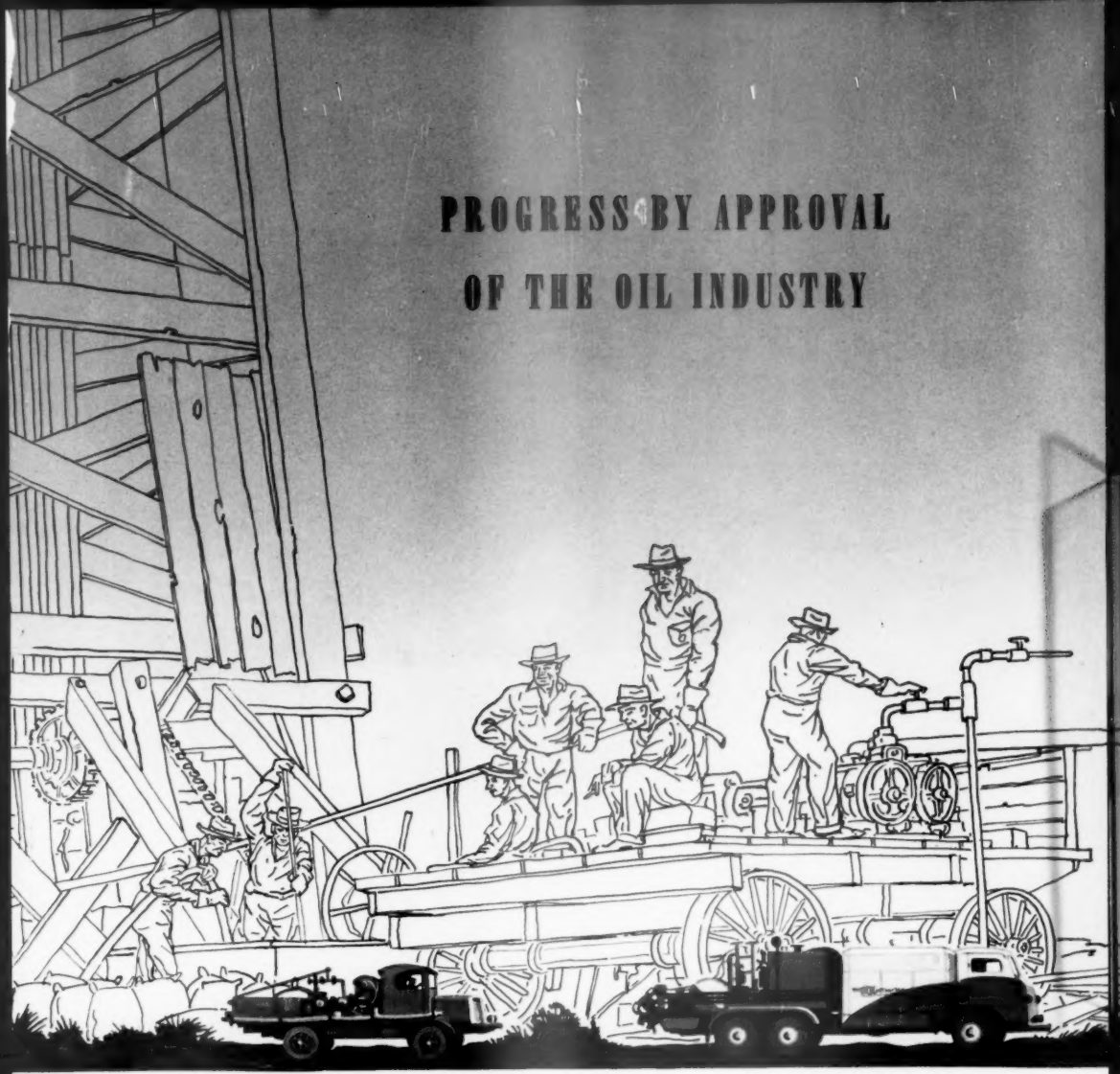
PROGRESS BY APPROVAL OF THE OIL INDUSTRY



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